



Search for new phenomena in dijet mass and angular distributions from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration ^{*}



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ABSTRACT

This Letter describes a model-agnostic search for pairs of jets (dijets) produced by resonant and non-resonant phenomena beyond the Standard Model in 3.6 fb^{-1} of proton–proton collisions with a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. The distribution of the invariant mass of the two leading jets is examined for local excesses above a data-derived estimate of the smoothly falling prediction of the Standard Model. The data are also compared to a Monte Carlo simulation of Standard Model angular distributions derived from the rapidity of the two jets. No evidence of anomalous phenomena is observed in the data, which are used to exclude, at 95% CL, quantum black holes with threshold masses below 8.3 TeV, 8.1 TeV, or 5.1 TeV in three different benchmark scenarios; resonance masses below 5.2 TeV for excited quarks, 2.6 TeV in a W' model, a range of masses starting from $m_{Z'} = 1.5$ TeV and couplings from $g_q = 0.2$ in a Z' model; and contact interactions with a compositeness scale below 12.0 TeV and 17.5 TeV respectively for destructive and constructive interference between the new interaction and QCD processes. These results significantly extend the ATLAS limits obtained from 8 TeV data. Gaussian-shaped contributions to the mass distribution are also excluded if the effective cross-section exceeds values ranging from approximately 50–300 fb for masses below 2 TeV to 2–20 fb for masses above 4 TeV.

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1. Introduction

The centre-of-mass energy of proton–proton (pp) collisions at the Large Hadron Collider (LHC) at CERN has been increased from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 13$ TeV, opening a new energy regime to observation.

New particles produced in LHC collisions must interact with the constituent partons of the proton. Consequently, the new particles can also produce partons in the final state. Final states including partons often dominate in models of new phenomena beyond the Standard Model (BSM). The partons shower and hadronize, creating collimated jets of particles carrying approximately the four-momenta of the partons. The total production rates for two-jet (dijet) BSM signals can be large, allowing searches for anomalous dijet production to test for such signals with a relatively small data sample, even at masses that constitute significant fractions of the total hadron collision energy.

In the Standard Model (SM), hadron collisions produce jet pairs primarily via $2 \rightarrow 2$ parton scattering processes governed by quantum chromodynamics (QCD). Far above the confinement scale of QCD (≈ 1 GeV), jets emerge from collisions with large transverse

momenta, p_T , perpendicular to the direction of the incident partons. For the data analysed here, QCD predicts a smoothly falling dijet invariant mass distribution, m_{jj} . New states decaying to two jets may introduce localized excesses in this distribution. In QCD, due to t -channel poles in the cross-sections for the dominant scattering processes, most dijet production occurs at small angles θ^* , defined as the polar angle in the dijet centre-of-mass frame.¹ Many theories of BSM physics predict additional dijet production with a significant population of jets produced at large angles with respect to the beam; for reviews see Refs. [1,2]. The search reported in this Letter exploits these generic features of BSM signals in an analysis of the m_{jj} and angular distributions.

As is common, a rapidity $y = \ln((E + p_z)/(E - p_z))/2$ is defined for each of the outgoing partons, where E is its energy and p_z is the component of its momentum along the beam line.² Each incoming parton carries a fraction (Bjorken x) of the mo-

¹ Since, experimentally, the two partons cannot be distinguished, θ^* is always taken between 0 and $\pi/2$ with respect to the beam.

² ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam line. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms

^{*} E-mail address: atlas.publications@cern.ch.

momentum of the proton. A momentum imbalance between the two partons boosts the centre-of-mass frame of the collision relative to the laboratory frame along the z direction by $y_B = \ln(x_1/x_2)/2 = (y_3 + y_4)/2$, where y_B is the rapidity of the boosted centre-of-mass frame, x_1 and x_2 are the fractions of the proton momentum carried by each parton and y_3 and y_4 are the rapidities of the outgoing partons in the detector frame. Differences between two rapidities are invariant under such Lorentz boosts, hence the following function of the rapidity difference $y^* = (y_3 - y_4)/2$ between the two jets,

$$\chi = e^{2|y^*|} \sim \frac{1 + \cos \theta^*}{1 - \cos \theta^*},$$

is the same in the detector frame as in the partonic centre-of-mass frame. In the centre-of-mass frame, the two partons have rapidity $\pm y^*$.

The variable χ is constructed such that in the limit of massless parton scattering, and when only t -channel scattering contributes to the partonic cross-section, the angular distribution $dN/d\chi$ is approximately independent of χ . The measured shapes of the observed $dN/d\chi$ distributions differ from the parton-level distributions because the observed distributions convolve the parton-level distributions with non-uniform parton momentum distributions in x_1 and x_2 . Restricting the range of two-parton invariant mass and placing an upper cut on y_B reduces these differences.

Prior searches of dijet distributions with lower-energy hadron collisions at the SppS [3–5], the Tevatron [6,7], and the LHC at $\sqrt{s} = 7$ –8 TeV [8–19] and recently at 13 TeV [20], did not find BSM phenomena. This Letter presents an analysis of 3.6 fb^{-1} of proton–proton collision LHC data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector, focusing on the distributions of m_{jj} and χ with methods based on those used by Refs. [17,19].

2. The ATLAS detector

The ATLAS experiment [21] at the LHC is a multi-purpose particle detector with a forward–backward symmetric cylindrical geometry with layers of tracking, calorimeter, and muon detectors over nearly the entire solid angle around the pp collision point. The directions and energies of high- p_T hadronic jets are measured using silicon tracking detectors and straw tubes detecting transition radiation, finely segmented hadronic and electromagnetic calorimeters, and a muon spectrometer. A steel/scintillator-tile calorimeter provides hadronic energy measurements for the pseudorapidity range $|\eta| < 1.7$. A lead/liquid-argon (LAr) calorimeter provides electromagnetic (EM) energy measurements with higher granularity within the region $|\eta| < 3.2$. The end-cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to 100 kHz. This is followed by a software-based trigger that reduces the rate of events recorded to 1 kHz.

3. Data selection

Collision events are recorded using a trigger requiring the presence of at least one jet reconstructed in the software-based trigger with a p_T of at least 360 GeV. Groups of contiguous calorimeter cells (topological clusters) are formed based on the significance of

the energy deposit over calorimeter noise [22]. Topological clusters are grouped into jets using the anti- k_t algorithm [23,24] with radius parameter $R = 0.4$. Jet four-momenta are computed by summing over the topological clusters that constitute each jet, treating the energy of each cluster as a four-momentum with zero mass. The reconstruction efficiency for jets with p_T above 20 GeV is 100%. Jet calibrations derived from $\sqrt{s} = 13$ TeV simulation, and collision data taken at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV, are used to correct the jet energies and directions to those of the particles from the hard-scatter interaction. This calibration procedure, described in Refs. [25–27], is improved by a data-derived correction to the relative calibration of jets in the central and the forward regions. The dijet mass resolution is 2.4% and 2%, for dijet masses of 2 and 5 TeV respectively. The jet energy scale uncertainty from 8 TeV data is complemented by systematic uncertainties covering the differences between 8 TeV and 13 TeV data. The total jet energy scale uncertainty is 1% for central jets with p_T of 500 GeV, and 3% for jets of 2 TeV. Analysis of jet data at 13 TeV using the *in situ* techniques described in Ref. [28] confirms the jet calibration and uncertainty estimates. Beyond the p_T range of the *in situ* techniques, for the quantities used to calibrate jets as well as other kinematic quantities, the data agree with simulation within quoted uncertainties.

Events containing at least two jets are selected for offline analysis if the p_T of the leading and subleading jets is greater than 440 GeV and 50 GeV respectively. This requirement ensures a trigger efficiency of at least 99.5% for collisions with $|y^*| < 1.7$ and removes a negligible number of events from unbalanced dijet events originating from additional interactions within the same bunch crossing or jet resolution tails. Events are discarded from the search if any of the three leading jets with $p_T > 50$ GeV is compatible with non-collision background or calorimeter noise [29].

4. Simulated collisions

For this search, events from QCD processes are simulated with PYTHIA 8 [30] using the A14 [31] set of tuned parameters for the underlying event and the leading-order NNPDF2.3 [32] parton distribution functions (PDFs). The renormalization and factorization scales are set to the average p_T of the two leading jets. Detector effects are simulated using GEANT4 [33] within the ATLAS software infrastructure [34]. The same software used to reconstruct data was also used to reconstruct simulated events. The simulated events are used to predict the angular distribution from QCD processes and for qualitative comparisons to kinematic distributions in data.

PYTHIA 8 calculations use matrix elements that are at leading order in the QCD coupling constant with simulation of higher-order contributions partially covered by the parton shower (PS) modelling. They also include modelling of hadronization effects. The distributions of events predicted by PYTHIA 8 are reweighted to the next-to-leading-order (NLO) predictions of NLOJET++ [35–37] using mass- and χ -dependent correction factors defined as in Ref. [19]. The correction factors modify the shape of the angular distributions at the level of 15% at low values of χ and high values of m_{jj} . The correction is 5% or less at the highest values of χ . The PYTHIA 8 predictions also omit electroweak effects. These are included as additional mass- and χ -dependent correction factors [38] that are unity at low m_{jj} and differ from unity by up to 3% in the $m_{jj} > 3.4$ TeV region.

BSM signal samples of excited quarks [39,40], new heavy vector bosons [41–43], quantum black holes [44–46] and contact interactions [47–49] are simulated and reconstructed using the same procedure as for QCD processes. The models and the parameters chosen for generation are described in Section 7.

of the polar angle θ as $\eta = -\text{Ln}(\tan(\theta/2))$. It is equivalent to the rapidity for massless particles.

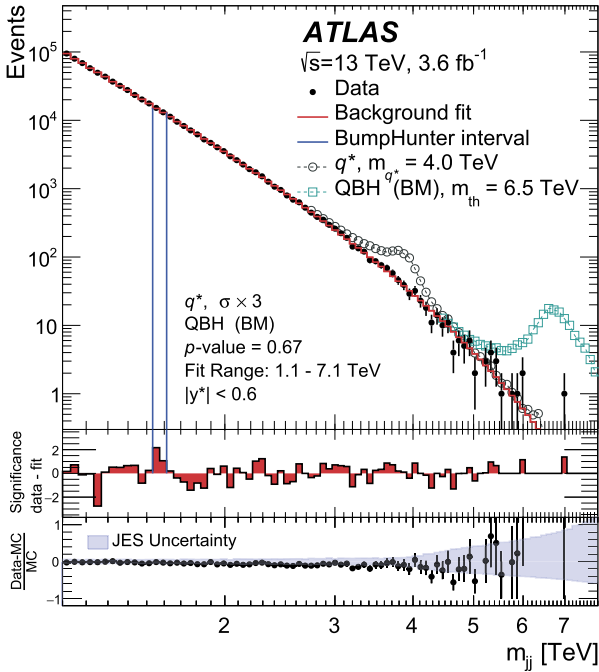


Fig. 1. The reconstructed dijet mass distribution (filled points) for events with $|y^*| < 0.6$ and $p_T > 440$ (50) GeV for the leading (subleading) jets. The solid line depicts the fit to Eq. (1), as discussed in the text. Predictions for an excited quark and a quantum black hole signal predicted by the BLACKMAX generator (QBH BM) are shown above the fit, normalized to the predicted cross-section. The vertical lines indicate the most discrepant interval identified by the BUMP Hunter algorithm, for which the p -value is stated in the figure. The middle panel shows the bin-by-bin significances of the data-fit differences, considering only statistical uncertainties. The lower panel shows the relative differences between the data and the prediction of PYTHIA 8 simulation of QCD processes, corrected for NLO and electroweak effects, and is shown purely for comparison. The shaded band denotes the experimental uncertainty in the jet energy scale calibration.

5. Selection for the mass distribution analysis

The m_{jj} distribution of events with $|y^*| < 0.6$ ($\chi < 3.3$) is analysed for evidence of contributions from resonant BSM phenomena. The requirement on $|y^*|$ reduces the background from QCD processes. To avoid kinematic bias from the y^* and p_T selections described above, the analysis is confined to $m_{jj} > 1.1$ TeV.

Fig. 1 shows the observed m_{jj} distribution for the resonance selection, overlaid with examples of the signals described in Section 7. The bin widths are chosen to approximate the m_{jj} resolution as derived from the simulation of QCD processes, and therefore widen as the mass increases. The largest value of m_{jj} measured is 6.9 TeV.

To estimate the SM background, the ansatz,

$$f(z) = p_1(1-z)^{p_2}z^{p_3}, \quad (1)$$

where $z \equiv m_{jj}/\sqrt{s}$, is fit to the m_{jj} distribution in Fig. 1 to obtain the parameters p_i . The fit range is 1.1–7.1 TeV. CDF, CMS, and ATLAS dijet searches such as those described in Refs. [6,8,13,14,17] have found that expressions similar to Eq. (1) describe dijet mass distributions observed at lower collision energies. The ansatz also describes leading-order and next-to-leading order simulations of QCD dijet production at $\sqrt{s} = 13$ TeV. A log-likelihood-ratio statistic employing Wilks's theorem [50] was used to determine if the background estimation would be significantly improved by an additional degree of freedom. With the current dataset, Eq. (1) was found to be sufficient.

Fig. 1 also shows the result of the fit. The fit describes the observed data with a p -value of 0.87, using a Poisson likelihood test

statistic. The middle panel of the figure shows the significances of bin-by-bin differences between the data and the fit. These Gaussian significances are calculated from the Poisson probability, considering only statistical uncertainties. The lower panel compares the data to the prediction of PYTHIA 8 simulation of QCD processes, corrected for NLO and electroweak effects. Even though it is not used in the analysis of the m_{jj} distribution, the simulation is shown to be in good agreement with the data.

The uncertainty in values of the parameters in Eq. (1) is evaluated by fitting them to pseudo-data drawn via Poisson fluctuations around the fitted background model. The uncertainty in the prediction in each m_{jj} bin is taken to be the root mean square of the function value for all pseudo-experiments in that bin. To estimate an uncertainty due to the choice of the background parameterization, a parameterization with one additional degree of freedom, $z^{p_4} \log z$, is compared to the nominal ansatz, and the difference is taken as an uncertainty. The prediction of the m_{jj} distribution does not involve simulated collisions and thus is not affected by theoretical or experimental uncertainties.

The statistical significance of any localized excess in the m_{jj} distribution is quantified using the BUMP Hunter algorithm [51,52]. The algorithm compares the binned m_{jj} distribution of the data to the fitted background estimate, considering contiguous mass intervals in all possible locations, from a width of two bins to a width of half of the distribution. For each interval in the scan, it computes the significance of any excess found. The algorithm identifies the interval 1.53–1.61 TeV, indicated by the two vertical lines in Fig. 1, as the most discrepant interval. The statistical significance of this outcome is evaluated using the ensemble of possible outcomes across all intervals scanned, by applying the algorithm to many pseudo-data samples drawn randomly from the background fit. Without including systematic uncertainties, the probability that fluctuations of the background model would produce an excess at least as significant as the one observed in the data, anywhere in the distribution, is 0.67. Thus, there is no evidence of a localized contribution to the mass distribution from BSM phenomena.

6. Selection for the angular distributions analysis

The $dN/d\chi$ (angular) distributions of events with $|y^*| < 1.7$ (i.e. $\chi < 30.0$) and $|y_B| < 1.1$ are also analysed for contributions from BSM signals. Fig. 2 shows the angular distributions of the data in different m_{jj} ranges, the SM prediction for the shape of the angular distributions, and examples of the signals described in Section 7. The data with $m_{jj} < 2.5$ TeV are discarded to remove bias from the kinematic selections described earlier. The highest m_{jj} measured is 7.9 TeV. The SM prediction is obtained from simulation, as described in Section 4. In the analysis, the prediction in each m_{jj} range is normalized to match the integral of the data in that range.

Theoretical uncertainties in simulations of the angular distributions from QCD processes are estimated as described in Ref. [19]. The effect on the QCD prediction of varying the PDFs is estimated using NLOJET++ with three different PDF sets: CT10 [53], MSTW2008 [54] and NNPDF23 [32]. As the choice of PDF largely affects the total cross-section rather than the shape of the χ distributions, these uncertainties are negligible ($< 1\%$). The uncertainty due to the choice of renormalization and factorization scales was estimated using NLOJET++ by varying each independently up and down by a factor two, excluding opposite variations. The resulting uncertainty, taken as the envelope of the variations in the normalized χ distributions, depends on both m_{jj} and χ , rising to 20% at the smallest χ values at high m_{jj} values. The statistical uncertainty of the simulated NLO corrections is less than 1%. The dominant experimental uncertainty in the predictions of the χ distributions is

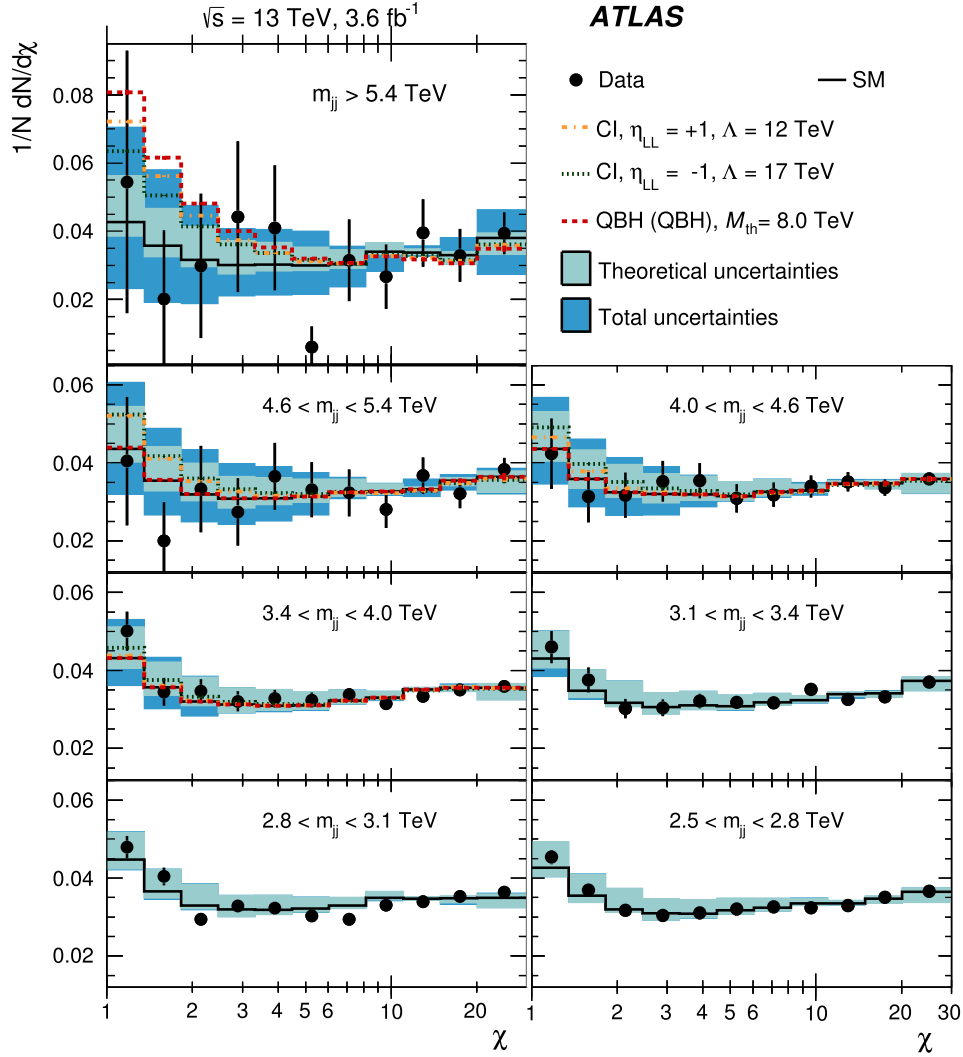


Fig. 2. Reconstructed distributions of the dijet angular variable χ in different regions of the dijet invariant mass m_{jj} for events with $|y^*| < 1.7$, $|y_B| < 1.1$ and $p_T > 440$ (50) GeV for the leading (subleading) jets. Shown are the data (points), corrected NLO predictions (solid lines), and examples of the contact interaction (CI) and quantum black hole (QBH) signals discussed in the text. The theoretical uncertainties and the total theoretical and experimental uncertainties in the predictions are displayed as shaded bands around the SM prediction.

the jet energy scale uncertainty, with an impact of at most 25% at high m_{jj} values. The uncertainty in the jet energy resolution has negligible impact. The theoretical uncertainties and the total uncertainties are displayed as shaded bands around the prediction.

The CL_s technique [55,56] is used to test the compatibility of the χ distribution with the SM prediction and with the BSM signals discussed in Section 7, using a combined fit in four coarse m_{jj} bins covering $m_{jj} > 3.4$ TeV. No significant deviation of the data from the background-only hypothesis is observed, with a CL_b of 0.35.

7. Signal models

The data are used to constrain several of the many BSM models that predict dijet excesses. Quantum black holes, excited quarks, and W' and Z' bosons would produce peaks in the m_{jj} distribution. Contact interactions would introduce smooth changes in the high-mass tail of the m_{jj} distribution that could be detected in the analysis of the χ distributions. The signal models are simulated using the parton-level generators indicated below, in an identical manner to QCD processes, using the same PDFs and parameters for non-perturbative effects, except where noted otherwise.

The LHC could produce black holes with masses at or above the fundamental scale of gravity, M_D , if that scale is lowered to a few TeV by the existence of extra spatial dimensions [2,44,45,57–60]. High-multiplicity final states from thermalizing black holes are explored at $\sqrt{s} = 13$ TeV by ATLAS in Ref. [61]. This analysis explores quantum black holes (QBHs), which would be produced near M_D and decay into a few particles rather than high-multiplicity final states [44–46,62], appearing in the m_{jj} distribution as an excess localized at the threshold mass for the quantum black hole production, M_{th} . Here, production and decay to two jets is simulated using the QBH generator [63] or the BLACKMAX generator [46],³ assuming an Arkani-Hamed–Dimopoulos–Dvali (ADD) scenario [64, 65] with $M_D = M_{th}$ and a number of extra dimensions $n = 6$, as in Ref. [17], and a Randall–Sundrum scenario (RS1) [66] with $n = 1$ using the QBH generator. In these models, the branching ratio to dijets is greater than 96%. The acceptance times efficiency of the resonance (angular) selection for a quantum black hole with a

³ Black holes decay thermally to non-rotating QBH in BLACKMAX, while the decay products of the QBH generator are dictated by local gauge symmetries of the SM.

threshold mass of 6.5 TeV is 53% (92%) for both generators. The PDFs used are CTEQ6L1 [67].

Excited quarks (q^*) [39,40] are predicted in models of compositeness and are a benchmark for quark–gluon resonances [8,9,14,15]. The q^* model is simulated with PYTHIA 8, assuming spin-1/2 excited quarks with coupling constants the same as for SM quarks. As in Ref. [40], the compositeness scale is set equal to the excited quark mass, m_{q^*} , and the SU(3), SU(2), and U(1) coupling multipliers $f_s = f = f' = 1$. The renormalization and factorization scales are set to the average p_T of the two leading jets. In the simulation, only the decay of the excited quark to a gluon and an up- or down-type quark is modelled; this corresponds to a branching ratio of 85%. Before parton shower effects are taken into account, the intrinsic width of the q^* signals is comparable to the detector resolution. The resonance selection acceptance times efficiency for a q^* with a mass of 4 TeV is 58%.

Additional spin-1 W' and Z' bosons often arise in the symmetry breaking of extended gauge theories. A W' model [41] with V – A SM couplings and a corresponding branching ratio to dijets of 75% is considered. In this analysis, events are simulated in PYTHIA 8 and decays are restricted to quark–antiquark pairs with all six quark flavours included. Events including top decays were not removed from the analysis, resulting in conservative limits. A leptophobic Z' model [42] is also simulated, with matrix elements calculated in MADGRAPH 5 [68] and parton showering performed in PYTHIA 8. The Z' model assumes axial-vector couplings to all SM quarks and to a Dirac fermion dark matter candidate. No interference with the SM is simulated for either the W' or the Z' model and decays involving top quarks are included. The Z' model considered follows a scenario [43] where its decays to dark matter are negligible, hence the dijet production rate and resonance width depend only on the coupling to quarks, g_q , and the mass of the resonance $m_{Z'}$. Before parton shower effects are considered, the intrinsic width of the W' and Z' signals range from 0.05% for a Z' with a mass of 1.5 TeV and $g_q = 0.1$ to 10% for a Z' with a mass of 3.5 TeV and $g_q = 0.5$. The resonance selection acceptance times efficiency for a mass of 3 TeV is 40% for the W' model and 47% for the Z' model with $g_q = 0.2$.

Results are also provided as limits on the cross-section times acceptance times branching ratio to two jets, $\sigma \times A \times \text{BR}$, of a hypothetical signal that produces a Gaussian contribution to the observed m_{jj} distribution. For sufficiently narrow resonances, these results may be used to set limits in BSM models beyond those considered explicitly in this Letter. These limits should be used when PDF and non-perturbative effects can be safely truncated or neglected and, after applying the resonance selection, the reconstructed m_{jj} distribution predicted by the model approaches a Gaussian distribution. Predicted BSM signals with an intrinsic width much smaller than 5% should be compared to the limit curve for width equal to the experimental resolution. Predicted signals with larger widths should be compared with the limit that corresponds most closely to the width of the Gaussian contribution predicted by the model. More instructions can be found in Appendix A of Ref. [17].

For all signals described above, the following systematic uncertainties are included in the limit setting: jet energy scale, PDF and uncertainties due to higher-order corrections, luminosity, and statistical uncertainties of the simulated events. The jet energy uncertainty is up to 10%. On average, the PDF uncertainty affects the angular distributions by 1%. The uncertainty in the integrated luminosity is $\pm 9\%$. It is derived, following a method similar to that detailed in Ref. [69], from a preliminary calibration of the luminosity scale using a pair of x – y beam-separation scans performed in June 2015.

The dijet distributions can also be modified by new mediating particles with a mass much higher than can be probed directly. A four-fermion effective field theory (contact interaction) [47–49] characterized by a single energy scale Λ can then be used to describe these effects:

$$L_{qq} = \frac{2\pi}{\Lambda^2} [\eta_{LL} (\bar{q}_L \gamma^\mu q_L) (\bar{q}_L \gamma_\mu q_L) + \eta_{RR} (\bar{q}_R \gamma^\mu q_R) (\bar{q}_R \gamma_\mu q_R) + 2\eta_{RL} (\bar{q}_R \gamma^\mu q_R) (\bar{q}_L \gamma_\mu q_L)],$$

where the quark fields have L and R chiral projections and the coefficients η_{LL} , η_{RR} , and η_{RL} turn on and off various interactions. Contact interactions with a non-zero left-chiral colour-singlet coupling ($\eta_{LL} = \pm 1$, $\eta_{RL} = \eta_{RR} = 0$) are simulated using PYTHIA 8. This type of coupling is chosen because its angular distributions are representative of those of other BSM models. Interference of the signal model with the SM process $q\bar{q} \rightarrow q\bar{q}$ is included. Events are simulated for both constructive and destructive interference with $\Lambda = 7$ TeV. From this sample, the angular distributions for other values of Λ are obtained using the fact that the interference term is proportional to $1/\Lambda^2$ and the pure contact-interaction cross-section is proportional to $1/\Lambda^4$. The PYTHIA 8 signal prediction is reweighted to the NLO cross-sections provided by CI-JET [70]. Uncertainties in the prediction of the angular distributions for contact-interaction signals are obtained in the same manner as for QCD processes.

8. Limits

Starting from the m_{jj} distribution obtained with the resonance selection, a Bayesian method [14] is applied to the data and simulation of signals at a series of discrete masses to set 95% credibility-level upper limits on the cross-section times acceptance for the signals described above. The method uses a constant prior for signal cross-section and Gaussian priors for nuisance parameters corresponding to systematic uncertainties. The expected limits are calculated using pseudo-experiments generated from the maximum-likelihood values for parameters of the background-only model in Eq. (1) using the full systematic uncertainties in both the signal and background models. The limit is interpolated logarithmically between the discrete masses to create curves continuous in signal mass. The mass limits for each of those models are shown in Figs. 3 and 4 and Table 1. No uncertainty is included for the cross-section of the signals considered.

Fig. 5 shows limits on the Gaussian contributions to the observed m_{jj} distribution obtained for a mean mass m_G and four different widths, from a width equal to the detector mass resolution to a width of 15% of the mean of the Gaussian mass distribution. Limits are set only when m_G is within 1.1 TeV–6.9 TeV and separated by at least twice the width of the Gaussian from the endpoints of this range. Intrinsically narrow resonances with effective cross-sections exceeding values ranging from approximately 50–300 fb for masses below 2 TeV to 2–20 fb for masses above 4 TeV are excluded. As the width increases, the expected signal contribution is distributed across more bins. Therefore wider signals are affected less than narrower signals by statistical fluctuations of the data in a single bin.

Starting from the χ distribution obtained with the angular selection, the CL_s is calculated for signal contributions from contact interactions and quantum black holes, using the background predicted by the SM simulations as the null hypothesis. The asymptotic approximation [71] of a profile likelihood ratio is used to set 95% confidence-level limits in the contact interaction and quantum black hole models. A combined fit is performed on the four highest- m_{jj} regions of Fig. 2. The correlation of the systematic uncertainties between the regions is taken into account and the max-

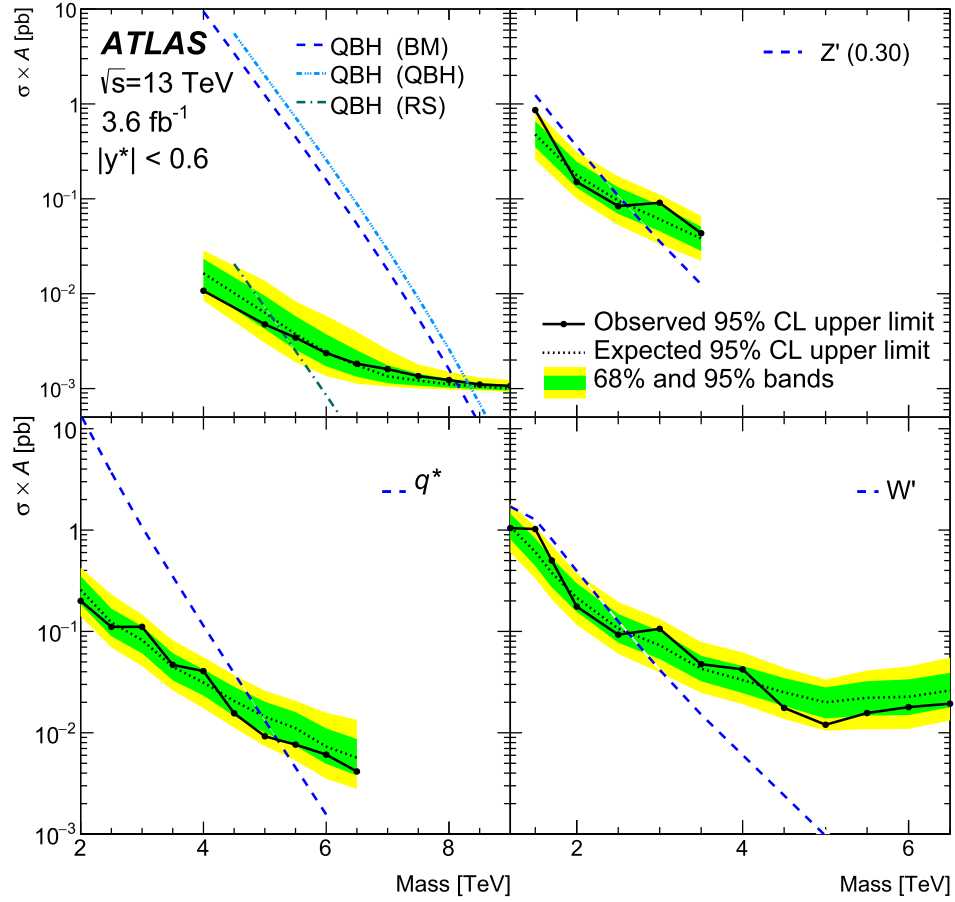


Fig. 3. The 95% credibility-level upper limits obtained from the m_{jj} distribution on cross-section, σ , times acceptance, A , for the models described in the text. Clockwise from top left: quantum black holes with $n = 6$ generated with BLACKMAX (QBH (BM)), and with $n = 6$ and $n = 1$ with QBH (denoted by QBH (QBH) and QBH (RS), respectively), Z' with $g_q = 0.3$, W' , and q^* .

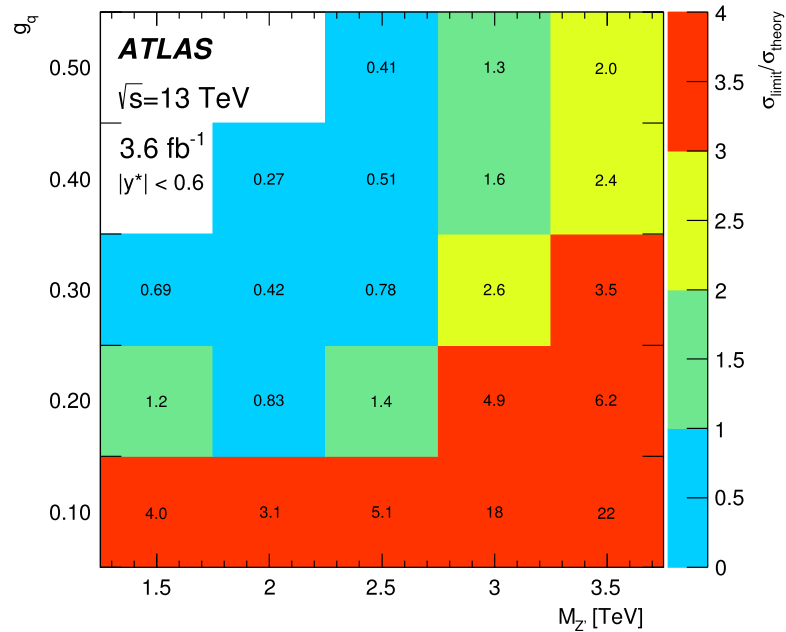


Fig. 4. The ratio of 95% credibility-level upper limits to predicted cross-sections with respect to the Z' model predictions described in the text, as a function of the coupling to quarks, g_q , and the mass, $M_{Z'}$, obtained from the m_{jj} distribution. Since for a given mass higher couplings have higher cross sections and would therefore be excluded if lower couplings are excluded, the limits are not calculated in the white area.

Table 1

The 95% credibility-level lower limit on the mass of quantum black holes, W' models and excited quarks from the resonance selection, and the 95% confidence-level lower limit on the scale of contact interactions for constructive ($\eta_{LL} = -1$) and destructive ($\eta_{LL} = +1$) from the angular selection. Limits on the Z' model are provided in Fig. 4. For comparison between the results from the two selections, the corresponding limit on quantum black holes for the angular selection is 8.1 TeV for the QBH $n = 6$ model. The Run 1 limits shown above were obtained in Refs. [17,19].

Model	95% CL exclusion limit		
	Run 1 observed	Observed 13 TeV	Expected 13 TeV
Quantum black holes, ADD (BLACKMAX generator)	5.6 TeV	8.1 TeV	8.1 TeV
Quantum black holes, ADD (QBH generator)	5.7 TeV	8.3 TeV	8.3 TeV
Quantum black holes, RS (QBH generator)	–	5.3 TeV	5.1 TeV
Excited quark	4.1 TeV	5.2 TeV	4.9 TeV
W'	2.5 TeV	2.6 TeV	2.6 TeV
Contact interactions ($\eta_{LL} = +1$)	8.1 TeV	12.0 TeV	12.0 TeV
Contact interactions ($\eta_{LL} = -1$)	12.0 TeV	17.5 TeV	18.1 TeV

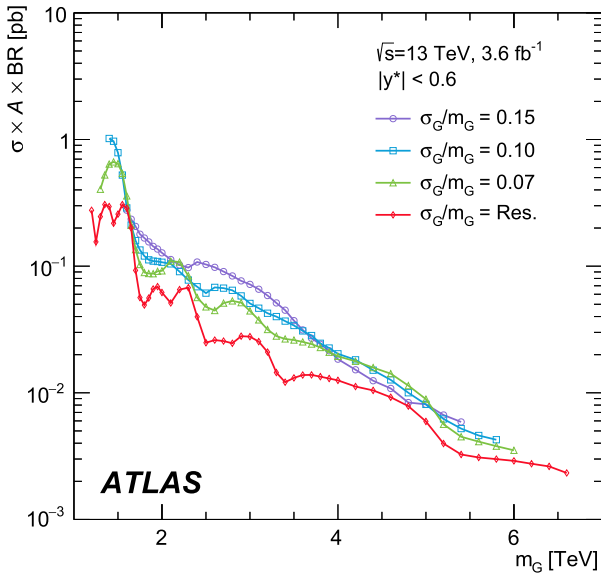


Fig. 5. The 95% credibility-level upper limits obtained from the m_{jj} distribution on cross-section times acceptance times branching ratio to two jets, $\sigma \times A \times BR$, for a hypothetical signal with a cross-section σ_G that produces a Gaussian contribution to the observed m_{jj} distribution, as a function of the mean mass of the Gaussian distribution, m_G . Limits are obtained for four different widths, from a width equal to the detector mass resolution (“Res.”), 3%–2% depending on m_{jj} probed, to 15% of the mean of the Gaussian mass distribution.

imum likelihood values of the nuisance parameters do not differ significantly from the expectation. The validity of the asymptotic approximation was confirmed using toy simulations. The bounds on contact interactions are shown in Fig. 6 and in Table 1. Limits obtained from the angular distributions on quantum black hole signals are similar to the limits obtained from the m_{jj} distribution.

9. Conclusion

No evidence of phenomena beyond the Standard Model was uncovered in this search using dijet events in 3.6 fb^{-1} of proton–proton collisions with a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector at the Large Hadron Collider. The dijet invariant mass distribution exhibits no significant local excesses above a data-derived estimate of the smoothly falling distribution predicted by the Standard Model. The dijet angular distributions also agree with a Monte Carlo simulation of the SM. With the resonance selection, the analysis excludes at 95% credibility level several types of signals, as predicted by models of quantum black holes, excited quarks, W' and Z' bosons. It also

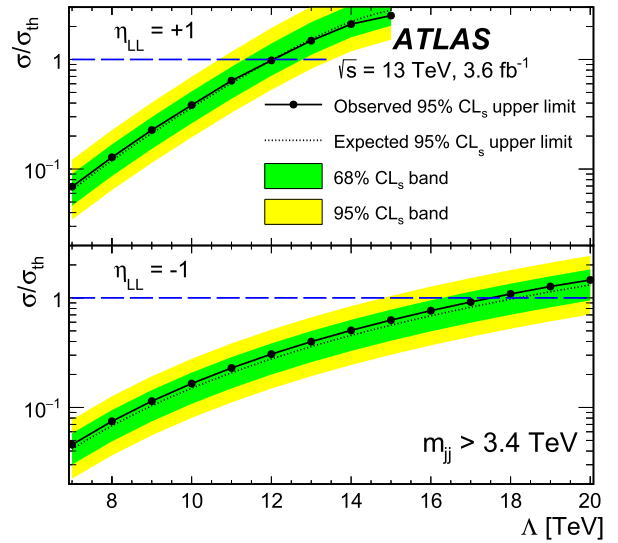


Fig. 6. Ratio of the observed and expected 95% confidence-level upper limits on the cross-section in the contact interaction model to the predicted cross-section σ/σ_{th} as a function of compositeness scale Λ , for (top) destructive and (bottom) constructive interference with QCD processes. The crossing of the observed and expected 95% confidence-level lines with the line at signal strength of one indicates observed and expected lower limits on Λ , respectively.

sets 95% credibility-level upper limits on the cross-section for new processes that would produce a Gaussian contribution to the dijet mass distribution. It excludes Gaussian contributions if the effective cross-section exceeds values ranging from approximately 50–300 fb for masses below 2 TeV to 2–20 fb for masses above 4 TeV. With the angular selection, 95% confidence-level lower limits are set on the compositeness scale of contact interactions at 12.0 TeV (17.5 TeV) for destructive (constructive) interference between the new interaction and QCD processes. These results significantly extend the ATLAS limits obtained from 8 TeV data.

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ATLAS Collaboration

G. Aad⁸⁷, B. Abbott¹¹⁴, J. Abdallah¹⁵², O. Abdinov¹¹, B. Abeloos¹¹⁸, R. Aben¹⁰⁸, M. Abolins⁹², O.S. AbouZeid¹⁵⁹, H. Abramowicz¹⁵⁴, H. Abreu¹⁵³, R. Abreu¹¹⁷, Y. Abulaiti^{147a,147b}, B.S. Acharya^{163a,163b,a}, L. Adamczyk^{39a}, D.L. Adams²⁶, J. Adelman¹⁰⁹, S. Adomeit¹⁰¹, T. Adye¹³², A.A. Affolder⁷⁶, T. Agatonovic-Jovin¹³, J. Agricola⁵⁵, J.A. Aguilar-Saavedra^{127a,127f}, S.P. Ahlen²³, F. Ahmadov^{67,b}, G. Aielli^{134a,134b}, H. Akerstedt^{147a,147b}, T.P.A. Åkesson⁸³, A.V. Akimov⁹⁷, G.L. Alberghi^{21a,21b}, J. Albert¹⁶⁸, S. Albrand⁵⁶, M.J. Alconada Verzini⁷³, M. Aleksa³¹, I.N. Aleksandrov⁶⁷, C. Alexa^{27b}, G. Alexander¹⁵⁴, T. Alexopoulos¹⁰, M. Alhroob¹¹⁴, G. Alimonti^{93a}, L. Alio⁸⁷, J. Alison³², S.P. Alkire³⁶, B.M.M. Allbrooke¹⁵⁰, B.W. Allen¹¹⁷, P.P. Allport¹⁸, A. Aloisio^{105a,105b}, A. Alonso³⁷, F. Alonso⁷³, C. Alpigiani¹³⁹, B. Alvarez Gonzalez³¹, D. Álvarez Piqueras¹⁶⁶, M.G. Alviggi^{105a,105b}, B.T. Amadio¹⁵, K. Amako⁶⁸, Y. Amaral Coutinho^{25a}, C. Amelung²⁴, D. Amidei⁹¹, S.P. Amor Dos Santos^{127a,127c}, A. Amorim^{127a,127b}, S. Amoroso³¹, N. Amram¹⁵⁴, G. Amundsen²⁴, C. Anastopoulos¹⁴⁰, L.S. Ancu⁵⁰, N. Andari¹⁰⁹, T. Andeen³², C.F. Anders^{59b}, G. Anders³¹, J.K. Anders⁷⁶, K.J. Anderson³², A. Andreazza^{93a,93b}, V. Andrei^{59a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁸, P. Anger⁴⁵, A. Angerami³⁶, F. Anghinolfi³¹, A.V. Anisenkov^{110,c}, N. Anjos¹², A. Annovi^{125a,125b}, M. Antonelli⁴⁸, A. Antonov⁹⁹, J. Antos^{145b}, F. Anulli^{133a}, M. Aoki⁶⁸, L. Aperio Bella¹⁸, G. Arabidze⁹², Y. Arai⁶⁸, J.P. Araque^{127a}, A.T.H. Arce⁴⁶, F.A. Arduh⁷³, J.-F. Arguin⁹⁶, S. Argyropoulos⁶⁴, M. Arik^{19a}, A.J. Armbruster³¹, L.J. Armitage⁷⁸, O. Arnaez³¹, H. Arnold⁴⁹, M. Arratia²⁹, O. Arslan²², A. Artamonov⁹⁸, G. Artoni¹²¹, S. Artz⁸⁵, S. Asai¹⁵⁶, N. Asbah⁴³, A. Ashkenazi¹⁵⁴, B. Åsman^{147a,147b}, L. Asquith¹⁵⁰, K. Assamagan²⁶, R. Astalos^{145a}, M. Atkinson¹⁶⁵, N.B. Atlay¹⁴², K. Augsten¹²⁹, G. Avolio³¹, B. Axen¹⁵, M.K. Ayoub¹¹⁸, G. Azuelos^{96,d}, M.A. Baak³¹, A.E. Baas^{59a}, M.J. Baca¹⁸, H. Bachacou¹³⁷, K. Bachas^{75a,75b}, M. Backes³¹, M. Backhaus³¹, P. Bagiacchi^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{34a}, J.T. Baines¹³², O.K. Baker¹⁷⁵, E.M. Baldin^{110,c}, P. Balek¹³⁰, T. Balestri¹⁴⁹, F. Balli⁸⁶, W.K. Balunas¹²³, E. Banas⁴⁰, Sw. Banerjee^{172,e}, A.A.E. Bannoura¹⁷⁴, L. Barak³¹, E.L. Barberio⁹⁰, D. Barberis^{51a,51b}, M. Barbero⁸⁷, T. Barillari¹⁰², M. Barisonzi^{163a,163b}, T. Barklow¹⁴⁴, N. Barlow²⁹, S.L. Barnes⁸⁶, B.M. Barnett¹³², R.M. Barnett¹⁵, Z. Barnovska⁵, A. Baroncelli^{135a}, G. Barone²⁴, A.J. Barr¹²¹, L. Barranco Navarro¹⁶⁶, F. Barreiro⁸⁴, J. Barreiro Guimarães da Costa^{34a}, R. Bartoldus¹⁴⁴, A.E. Barton⁷⁴, P. Bartos^{145a}, A. Basalae¹²⁴, A. Bassalat¹¹⁸, A. Basye¹⁶⁵, R.L. Bates⁵⁴, S.J. Batista¹⁵⁹, J.R. Batley²⁹, M. Battaglia¹³⁸, M. Bause^{133a,133b}, F. Bauer¹³⁷, H.S. Bawa^{144,f}, J.B. Beacham¹¹², M.D. Beattie⁷⁴, T. Beau⁸², P.H. Beauchemin¹⁶², R. Beccherle^{125a,125b}, P. Bechtel²², H.P. Beck^{17,g}, K. Becker¹²¹, M. Becker⁸⁵, M. Beckingham¹⁶⁹, C. Becot¹¹¹, A.J. Beddall^{19e}, A. Beddall^{19b}, V.A. Bednyakov⁶⁷, M. Bedognetti¹⁰⁸, C.P. Bee¹⁴⁹, L.J. Beemster¹⁰⁸, T.A. Beermann³¹, M. Begel²⁶, J.K. Behr¹²¹, C. Belanger-Champagne⁸⁹, A.S. Bell⁸⁰, W.H. Bell⁵⁰, G. Bella¹⁵⁴, L. Bellagamba^{21a}, A. Bellerive³⁰, M. Bellomo⁸⁸, K. Belotskiy⁹⁹,

O. Beltramello³¹, O. Benary¹⁵⁴, D. Bencheekroun^{136a}, M. Bender¹⁰¹, K. Bendtz^{147a,147b}, N. Benekos¹⁰, Y. Benhammou¹⁵⁴, E. Benhar Noccioli¹⁷⁵, J. Benitez⁶⁴, J.A. Benitez Garcia^{160b}, D.P. Benjamin⁴⁶, J.R. Bensinger²⁴, S. Bentvelsen¹⁰⁸, L. Beresford¹²¹, M. Beretta⁴⁸, D. Berge¹⁰⁸, E. Bergeaas Kuutmann¹⁶⁴, N. Berger⁵, F. Berghaus¹⁶⁸, J. Beringer¹⁵, C. Bernard²³, N.R. Bernard⁸⁸, C. Bernius¹¹¹, F.U. Bernlochner²², T. Berry⁷⁹, P. Berta¹³⁰, C. Bertella⁸⁵, G. Bertoli^{147a,147b}, F. Bertolucci^{125a,125b}, C. Bertsche¹¹⁴, D. Bertsche¹¹⁴, G.J. Besjes³⁷, O. Bessidskaia Bylund^{147a,147b}, M. Bessner⁴³, N. Besson¹³⁷, C. Betancourt⁴⁹, S. Bethke¹⁰², A.J. Bevan⁷⁸, W. Bhimji¹⁵, R.M. Bianchi¹²⁶, L. Bianchini²⁴, M. Bianco³¹, O. Biebel¹⁰¹, D. Biedermann¹⁶, R. Bielski⁸⁶, N.V. Biesuz^{125a,125b}, M. Biglietti^{135a}, J. Bilbao De Mendizabal⁵⁰, H. Bilokon⁴⁸, M. Bindi⁵⁵, S. Binet¹¹⁸, A. Bingul^{19b}, C. Bini^{133a,133b}, S. Biondi^{21a,21b}, D.M. Bjergaard⁴⁶, C.W. Black¹⁵¹, J.E. Black¹⁴⁴, K.M. Black²³, D. Blackburn¹³⁹, R.E. Blair⁶, J.-B. Blanchard¹³⁷, J.E. Blanco⁷⁹, T. Blazek^{145a}, I. Bloch⁴³, C. Blocker²⁴, W. Blum^{85,*}, U. Blumenschein⁵⁵, S. Blunier^{33a}, G.J. Bobbink¹⁰⁸, V.S. Bobrovnikov^{110,c}, S.S. Bocchetta⁸³, A. Bocci⁴⁶, C. Bock¹⁰¹, M. Boehler⁴⁹, D. Boerner¹⁷⁴, J.A. Bogaerts³¹, D. Bogavac¹³, A.G. Bogdanchikov¹¹⁰, C. Bohm^{147a}, V. Boisvert⁷⁹, T. Bold^{39a}, V. Boldea^{27b}, A.S. Boldyrev^{163a,163c}, M. Bomben⁸², M. Bona⁷⁸, M. Boonekamp¹³⁷, A. Borisov¹³¹, G. Borissov⁷⁴, J. Bortfeldt¹⁰¹, D. Bortoletto¹²¹, V. Bortolotto^{61a,61b,61c}, K. Bos¹⁰⁸, D. Boscherini^{21a}, M. Bosman¹², J.D. Bossio Sola²⁸, J. Boudreau¹²⁶, J. Bouffard², E.V. Bouhova-Thacker⁷⁴, D. Boumediene³⁵, C. Bourdarios¹¹⁸, N. Bousson¹¹⁵, S.K. Boutle⁵⁴, A. Boveia³¹, J. Boyd³¹, I.R. Boyko⁶⁷, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt⁵⁵, O. Brandt^{59a}, U. Bratzler¹⁵⁷, B. Brau⁸⁸, J.E. Brau¹¹⁷, H.M. Braun^{174,*}, W.D. Breaden Madden⁵⁴, K. Brendlinger¹²³, A.J. Brennan⁹⁰, L. Brenner¹⁰⁸, R. Brenner¹⁶⁴, S. Bressler¹⁷¹, T.M. Bristow⁴⁷, D. Britton⁵⁴, D. Britzger⁴³, F.M. Brochu²⁹, I. Brock²², R. Brock⁹², G. Brooijmans³⁶, T. Brooks⁷⁹, W.K. Brooks^{33b}, J. Brosamer¹⁵, E. Brost¹¹⁷, P.A. Bruckman de Renstrom⁴⁰, D. Bruncko^{145b}, R. Bruneliere⁴⁹, A. Bruni^{21a}, G. Bruni^{21a}, B.H. Brunt²⁹, M. Bruschi^{21a}, N. Bruscino²², P. Bryant³², L. Bryngemark⁸³, T. Buanes¹⁴, Q. Buat¹⁴³, P. Buchholz¹⁴², A.G. Buckley⁵⁴, I.A. Budagov⁶⁷, F. Buehrer⁴⁹, M.K. Bugge¹²⁰, O. Bulekov⁹⁹, D. Bullock⁸, H. Burckhart³¹, S. Burdin⁷⁶, C.D. Burgard⁴⁹, B. Burghgrave¹⁰⁹, K. Burka⁴⁰, S. Burke¹³², I. Burmeister⁴⁴, E. Busato³⁵, D. Büscher⁴⁹, V. Büscher⁸⁵, P. Bussey⁵⁴, J.M. Butler²³, A.I. Butt³, C.M. Buttar⁵⁴, J.M. Butterworth⁸⁰, P. Butti¹⁰⁸, W. Buttinger²⁶, A. Buzatu⁵⁴, A.R. Buzykaev^{110,c}, S. Cabrera Urbán¹⁶⁶, D. Caforio¹²⁹, V.M. Cairo^{38a,38b}, O. Cakir^{4a}, N. Calace⁵⁰, P. Calafiura¹⁵, A. Calandri⁸⁷, G. Calderini⁸², P. Calfayan¹⁰¹, L.P. Caloba^{25a}, D. Calvet³⁵, S. Calvet³⁵, T.P. Calvet⁸⁷, R. Camacho Toro³², S. Camarda⁴³, P. Camarri^{134a,134b}, D. Cameron¹²⁰, R. Caminal Armadans¹⁶⁵, C. Camincher⁵⁶, S. Campana³¹, M. Campanelli⁸⁰, A. Campoverde¹⁴⁹, V. Canale^{105a,105b}, A. Canepa^{160a}, M. Cano Bret^{34e}, J. Cantero⁸⁴, R. Cantrill^{127a}, T. Cao⁴¹, M.D.M. Capeans Garrido³¹, I. Caprini^{27b}, M. Caprini^{27b}, M. Capua^{38a,38b}, R. Caputo⁸⁵, R.M. Carbone³⁶, R. Cardarelli^{134a}, F. Cardillo⁴⁹, T. Carli³¹, G. Carlino^{105a}, L. Carminati^{93a,93b}, S. Caron¹⁰⁷, E. Carquin^{33a}, G.D. Carrillo-Montoya³¹, J.R. Carter²⁹, J. Carvalho^{127a,127c}, D. Casadei⁸⁰, M.P. Casado^{12,h}, M. Casolino¹², D.W. Casper⁶⁶, E. Castaneda-Miranda^{146a}, A. Castelli¹⁰⁸, V. Castillo Gimenez¹⁶⁶, N.F. Castro^{127a,i}, A. Catinaccio³¹, J.R. Catmore¹²⁰, A. Cattai³¹, J. Caudron⁸⁵, V. Cavaliere¹⁶⁵, D. Cavalli^{93a}, M. Cavalli-Sforza¹², V. Cavasinni^{125a,125b}, F. Ceradini^{135a,135b}, L. Cerda Alberich¹⁶⁶, B.C. Cerio⁴⁶, A.S. Cerqueira^{25b}, A. Cerri¹⁵⁰, L. Cerrito⁷⁸, F. Cerutti¹⁵, M. Cerv³¹, A. Cervelli¹⁷, S.A. Cetin^{19d}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁹, I. Chalupkova¹³⁰, Y.L. Chan^{61a}, P. Chang¹⁶⁵, J.D. Chapman²⁹, D.G. Charlton¹⁸, C.C. Chau¹⁵⁹, C.A. Chavez Barajas¹⁵⁰, S. Che¹¹², S. Cheatham⁷⁴, A. Chegwiddden⁹², S. Chekanov⁶, S.V. Chekulaev^{160a}, G.A. Chelkov^{67,j}, M.A. Chelstowska⁹¹, C. Chen⁶⁵, H. Chen²⁶, K. Chen¹⁴⁹, S. Chen^{34c}, S. Chen¹⁵⁶, X. Chen^{34f}, Y. Chen⁶⁹, H.C. Cheng⁹¹, Y. Cheng³², A. Cheplakov⁶⁷, E. Cheremushkina¹³¹, R. Cherkaoui El Moursli^{136e}, V. Chernyatin^{26,*}, E. Cheu⁷, L. Chevalier¹³⁷, V. Chiarella⁴⁸, G. Chiarelli^{125a,125b}, G. Chiodini^{75a}, A.S. Chisholm¹⁸, R.T. Chislett⁸⁰, A. Chitan^{27b}, M.V. Chizhov⁶⁷, K. Choi⁶², S. Chouridou⁹, B.K.B. Chow¹⁰¹, V. Christodoulou⁸⁰, D. Chromek-Burckhart³¹, J. Chudoba¹²⁸, A.J. Chuinard⁸⁹, J.J. Chwastowski⁴⁰, L. Chytka¹¹⁶, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, D. Cinca⁵⁴, V. Cindro⁷⁷, I.A. Cioara²², A. Ciochio¹⁵, F. Ciotto^{105a,105b}, Z.H. Citron¹⁷¹, M. Ciubancan^{27b}, A. Clark⁵⁰, B.L. Clark⁵⁸, P.J. Clark⁴⁷, R.N. Clarke¹⁵, C. Clement^{147a,147b}, Y. Coadou⁸⁷, M. Cobal^{163a,163c}, A. Coccaro⁵⁰, J. Cochran⁶⁵, L. Coffey²⁴, L. Colasurdo¹⁰⁷, B. Cole³⁶, S. Cole¹⁰⁹, A.P. Colijn¹⁰⁸, J. Collot⁵⁶, T. Colombo^{59c}, G. Compostella¹⁰², P. Conde Muiño^{127a,127b}, E. Coniavitis⁴⁹, S.H. Connell^{146b}, I.A. Connelly⁷⁹, V. Consorti⁴⁹, S. Constantinescu^{27b}, C. Conta^{122a,122b}, G. Conti³¹, F. Conventi^{105a,k}, M. Cooke¹⁵,

B.D. Cooper⁸⁰, A.M. Cooper-Sarkar¹²¹, T. Cornelissen¹⁷⁴, M. Corradi^{133a,133b}, F. Corriveau^{89,l}, A. Corso-Radu⁶⁶, A. Cortes-Gonzalez¹², G. Cortiana¹⁰², G. Costa^{93a}, M.J. Costa¹⁶⁶, D. Costanzo¹⁴⁰, G. Cottin²⁹, G. Cowan⁷⁹, B.E. Cox⁸⁶, K. Cranmer¹¹¹, S.J. Crawley⁵⁴, G. Cree³⁰, S. Crépé-Renaudin⁵⁶, F. Crescioli⁸², W.A. Cribbs^{147a,147b}, M. Crispin Ortuzar¹²¹, M. Cristinziani²², V. Croft¹⁰⁷, G. Crosetti^{38a,38b}, T. Cuhadar Donszelmann¹⁴⁰, J. Cummings¹⁷⁵, M. Curatolo⁴⁸, J. Cúth⁸⁵, C. Cuthbert¹⁵¹, H. Czirr¹⁴², P. Czodrowski³, S. D'Auria⁵⁴, M. D'Onofrio⁷⁶, M.J. Da Cunha Sargedas De Sousa^{127a,127b}, C. Da Via⁸⁶, W. Dabrowski^{39a}, T. Dai⁹¹, O. Dale¹⁴, F. Dallaire⁹⁶, C. Dallapiccola⁸⁸, M. Dam³⁷, J.R. Dandoy³², N.P. Dang⁴⁹, A.C. Daniells¹⁸, M. Danninger¹⁶⁷, M. Dano Hoffmann¹³⁷, V. Dao⁴⁹, G. Darbo^{51a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta⁶², W. Davey²², C. David¹⁶⁸, T. Davidek¹³⁰, M. Davies¹⁵⁴, P. Davison⁸⁰, Y. Davygora^{59a}, E. Dawe⁹⁰, I. Dawson¹⁴⁰, R.K. Daya-Ishmukhametova⁸⁸, K. De⁸, R. de Asmundis^{105a}, A. De Benedetti¹¹⁴, S. De Castro^{21a,21b}, S. De Cecco⁸², N. De Groot¹⁰⁷, P. de Jong¹⁰⁸, H. De la Torre⁸⁴, F. De Lorenzi⁶⁵, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis¹⁵⁰, A. De Santo¹⁵⁰, J.B. De Vivie De Regie¹¹⁸, W.J. Dearnaley⁷⁴, R. Debbe²⁶, C. Debenedetti¹³⁸, D.V. Dedovich⁶⁷, I. Deigaard¹⁰⁸, J. Del Peso⁸⁴, T. Del Prete^{125a,125b}, D. Delgove¹¹⁸, F. Deliot¹³⁷, C.M. Delitzsch⁵⁰, M. Deliyergiyev⁷⁷, A. Dell'Acqua³¹, L. Dell'Asta²³, M. Dell'Orso^{125a,125b}, M. Della Pietra^{105a,k}, D. della Volpe⁵⁰, M. Delmastro⁵, P.A. Delsart⁵⁶, C. Deluca¹⁰⁸, D.A. DeMarco¹⁵⁹, S. Demers¹⁷⁵, M. Demichev⁶⁷, A. Demilly⁸², S.P. Denisov¹³¹, D. Denysiuk¹³⁷, D. Derendarz⁴⁰, J.E. Derkaoui^{136d}, F. Derue⁸², P. Dervan⁷⁶, K. Desch²², C. Deterre⁴³, K. Dette⁴⁴, P.O. Deviveiros³¹, A. Dewhurst¹³², S. Dhaliwal²⁴, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²³, A. Di Domenico^{133a,133b}, C. Di Donato^{133a,133b}, A. Di Girolamo³¹, B. Di Girolamo³¹, A. Di Mattia¹⁵³, B. Di Micco^{135a,135b}, R. Di Nardo⁴⁸, A. Di Simone⁴⁹, R. Di Sipio¹⁵⁹, D. Di Valentino³⁰, C. Diaconu⁸⁷, M. Diamond¹⁵⁹, F.A. Dias⁴⁷, M.A. Diaz^{33a}, E.B. Diehl⁹¹, J. Dietrich¹⁶, S. Diglio⁸⁷, A. Dimitrievska¹³, J. Dingfelder²², P. Dita^{27b}, S. Dita^{27b}, F. Dittus³¹, F. Djama⁸⁷, T. Djobava^{52b}, J.I. Djuvsland^{59a}, M.A.B. do Vale^{25c}, D. Dobos³¹, M. Dobre^{27b}, C. Doglioni⁸³, T. Dohmae¹⁵⁶, J. Dolejsi¹³⁰, Z. Dolezal¹³⁰, B.A. Dolgoshein^{99,*}, M. Donadelli^{25d}, S. Donati^{125a,125b}, P. Dondero^{122a,122b}, J. Donini³⁵, J. Dopke¹³², A. Doria^{105a}, M.T. Dova⁷³, A.T. Doyle⁵⁴, E. Drechsler⁵⁵, M. Dris¹⁰, Y. Du^{34d}, J. Duarte-Campderros¹⁵⁴, E. Duchovni¹⁷¹, G. Duckeck¹⁰¹, O.A. Ducu^{27b}, D. Duda¹⁰⁸, A. Dudarev³¹, L. Dufлот¹¹⁸, L. Duguid⁷⁹, M. Dührssen³¹, M. Dunford^{59a}, H. Duran Yildiz^{4a}, M. Düren⁵³, A. Durglishvili^{52b}, D. Duschinger⁴⁵, B. Dutta⁴³, M. Dyndal^{39a}, C. Eckardt⁴³, K.M. Ecker¹⁰², R.C. Edgar⁹¹, W. Edson², N.C. Edwards⁴⁷, T. Eifert³¹, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁴, M. El Kacimi^{136c}, V. Ellajosyula⁸⁷, M. Ellert¹⁶⁴, S. Elles⁵, F. Ellinghaus¹⁷⁴, A.A. Elliot¹⁶⁸, N. Ellis³¹, J. Elmsheuser¹⁰¹, M. Elsing³¹, D. Emelianov¹³², Y. Enari¹⁵⁶, O.C. Endner⁸⁵, M. Endo¹¹⁹, J.S. Ennis¹⁶⁹, J. Erdmann⁴⁴, A. Ereditato¹⁷, G. Ernis¹⁷⁴, J. Ernst², M. Ernst²⁶, S. Errede¹⁶⁵, E. Ertel⁸⁵, M. Escalier¹¹⁸, H. Esch⁴⁴, C. Escobar¹²⁶, B. Esposito⁴⁸, A.I. Etievre¹³⁷, E. Etzion¹⁵⁴, H. Evans⁶², A. Ezhilov¹²⁴, L. Fabbri^{21a,21b}, G. Facini³², R.M. Fakhruddinov¹³¹, S. Falciano^{133a}, R.J. Falla⁸⁰, J. Faltova¹³⁰, Y. Fang^{34a}, M. Fanti^{93a,93b}, A. Farbin⁸, A. Farilla^{135a}, C. Farina¹²⁶, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁶⁹, P. Farthouat³¹, F. Fassi^{136e}, P. Fassnacht³¹, D. Fassouliotis⁹, M. Fauci Giannelli⁷⁹, A. Favareto^{51a,51b}, L. Fayard¹¹⁸, O.L. Fedin^{124,m}, W. Fedorko¹⁶⁷, S. Feigl¹²⁰, L. Feligioni⁸⁷, C. Feng^{34d}, E.J. Feng³¹, H. Feng⁹¹, A.B. Fenyuk¹³¹, L. Feremenga⁸, P. Fernandez Martinez¹⁶⁶, S. Fernandez Perez¹², J. Ferrando⁵⁴, A. Ferrari¹⁶⁴, P. Ferrari¹⁰⁸, R. Ferrari^{122a}, D.E. Ferreira de Lima⁵⁴, A. Ferrer¹⁶⁶, D. Ferrere⁵⁰, C. Ferretti⁹¹, A. Ferretto Parodi^{51a,51b}, F. Fiedler⁸⁵, A. Filipčič⁷⁷, M. Filipuzzi⁴³, F. Filthaut¹⁰⁷, M. Fincke-Keeler¹⁶⁸, K.D. Finelli¹⁵¹, M.C.N. Fiolhais^{127a,127c}, L. Fiorini¹⁶⁶, A. Firan⁴¹, A. Fischer², C. Fischer¹², J. Fischer¹⁷⁴, W.C. Fisher⁹², N. Flaschel⁴³, I. Fleck¹⁴², P. Fleischmann⁹¹, G.T. Fletcher¹⁴⁰, G. Fletcher⁷⁸, R.R.M. Fletcher¹²³, T. Flick¹⁷⁴, A. Floderus⁸³, L.R. Flores Castillo^{61a}, M.J. Flowerdew¹⁰², G.T. Forcolin⁸⁶, A. Formica¹³⁷, A. Forti⁸⁶, D. Fournier¹¹⁸, H. Fox⁷⁴, S. Fracchia¹², P. Francavilla⁸², M. Franchini^{21a,21b}, D. Francis³¹, L. Franconi¹²⁰, M. Franklin⁵⁸, M. Frate⁶⁶, M. Fraternali^{122a,122b}, D. Freeborn⁸⁰, S.M. Fressard-Batraneanu³¹, F. Friedrich⁴⁵, D. Froidevaux³¹, J.A. Frost¹²¹, C. Fukunaga¹⁵⁷, E. Fullana Torregrosa⁸⁵, T. Fusayasu¹⁰³, J. Fuster¹⁶⁶, C. Gabaldon⁵⁶, O. Gabizon¹⁷⁴, A. Gabrielli^{21a,21b}, A. Gabrielli¹⁵, G.P. Gach^{39a}, S. Gadatsch³¹, S. Gadomski⁵⁰, G. Gagliardi^{51a,51b}, P. Gagnon⁶², C. Galea¹⁰⁷, B. Galhardo^{127a,127c}, E.J. Gallas¹²¹, B.J. Gallop¹³², P. Gallus¹²⁹, G. Galster³⁷, K.K. Gan¹¹², J. Gao^{34b,87}, Y. Gao⁴⁷, Y.S. Gao^{144,f}, F.M. Garay Walls⁴⁷, C. García¹⁶⁶, J.E. García Navarro¹⁶⁶, M. Garcia-Sciveres¹⁵, R.W. Gardner³², N. Garelli¹⁴⁴, V. Garonne¹²⁰, A. Gascon Bravo⁴³, C. Gatti⁴⁸, A. Gaudiello^{51a,51b},

G. Gaudio^{122a}, B. Gaur¹⁴², L. Gauthier⁹⁶, I.L. Gavrilenko⁹⁷, C. Gay¹⁶⁷, G. Gaycken²², E.N. Gazis¹⁰, Z. Gece¹⁶⁷, C.N.P. Gee¹³², Ch. Geich-Gimbel²², M.P. Geisler^{59a}, C. Gemme^{51a}, M.H. Genest⁵⁶, C. Geng^{34b,n}, S. Gentile^{133a,133b}, S. George⁷⁹, D. Gerbaudo⁶⁶, A. Gershon¹⁵⁴, S. Ghasemi¹⁴², H. Ghazlane^{136b}, B. Giacobbe^{21a}, S. Giagu^{133a,133b}, P. Giannetti^{125a,125b}, B. Gibbard²⁶, S.M. Gibson⁷⁹, M. Gignac¹⁶⁷, M. Gilchriese¹⁵, T.P.S. Gillam²⁹, D. Gillberg³⁰, G. Gilles¹⁷⁴, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{163a,163c}, F.M. Giorgi^{21a}, F.M. Giorgi¹⁶, P.F. Giraud¹³⁷, P. Giromini⁵⁸, D. Giugni^{93a}, C. Giuliani¹⁰², M. Giulini^{59b}, B.K. Gjelsten¹²⁰, S. Gkaitatzis¹⁵⁵, I. Gkialas¹⁵⁵, E.L. Gkougkousis¹¹⁸, L.K. Gladilin¹⁰⁰, C. Glasman⁸⁴, J. Glatzer³¹, P.C.F. Glaysher⁴⁷, A. Glazov⁴³, M. Goblirsch-Kolb¹⁰², J. Godlewski⁴⁰, S. Goldfarb⁹¹, T. Golling⁵⁰, D. Golubkov¹³¹, A. Gomes^{127a,127b,127d}, R. Gonçalves^{127a}, J. Goncalves Pinto Firmino Da Costa¹³⁷, L. Gonella²², A. Gongadze⁶⁷, S. González de la Hoz¹⁶⁶, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁵⁰, L. Goossens³¹, P.A. Gorbounov⁹⁸, H.A. Gordon²⁶, I. Gorelov¹⁰⁶, B. Gorini³¹, E. Gorini^{75a,75b}, A. Gorišek⁷⁷, E. Gornicki⁴⁰, A.T. Goshaw⁴⁶, C. Gössling⁴⁴, M.I. Gostkin⁶⁷, C.R. Goudet¹¹⁸, D. Goujdami^{136c}, A.G. Goussiou¹³⁹, N. Govender^{146b}, E. Gozani¹⁵³, L. Graber⁵⁵, I. Grabowska-Bold^{39a}, P.O.J. Gradin¹⁶⁴, P. Grafström^{21a,21b}, J. Gramling⁵⁰, E. Gramstad¹²⁰, S. Grancagnolo¹⁶, V. Gratchev¹²⁴, H.M. Gray³¹, E. Graziani^{135a}, Z.D. Greenwood^{81,o}, C. Grefe²², K. Gregersen⁸⁰, I.M. Gregor⁴³, P. Grenier¹⁴⁴, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹³⁸, K. Grimm⁷⁴, S. Grinstein^{12,p}, Ph. Gris³⁵, J.-F. Grivaz¹¹⁸, S. Groh⁸⁵, J.P. Grohs⁴⁵, E. Gross¹⁷¹, J. Grosse-Knetter⁵⁵, G.C. Grossi⁸¹, Z.J. Grout¹⁵⁰, L. Guan⁹¹, J. Guenther¹²⁹, F. Guescini⁵⁰, D. Guest⁶⁶, O. Gueta¹⁵⁴, E. Guido^{51a,51b}, T. Guillemin⁵, S. Guindon², U. Gul⁵⁴, C. Gumpert³¹, J. Guo^{34e}, Y. Guo^{34b,n}, S. Gupta¹²¹, G. Gustavino^{133a,133b}, P. Gutierrez¹¹⁴, N.G. Gutierrez Ortiz⁸⁰, C. Gutsche⁴⁵, C. Guyot¹³⁷, C. Gwenlan¹²¹, C.B. Gwilliam⁷⁶, A. Haas¹¹¹, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{136e}, A. Hadeef⁸⁷, P. Haefner²², S. Hageböck²², Z. Hajduk⁴⁰, H. Hakobyan^{176,*}, M. Haleem⁴³, J. Haley¹¹⁵, D. Hall¹²¹, G. Halladjian⁹², G.D. Hallowell⁸⁷, K. Hamacher¹⁷⁴, P. Hamal¹¹⁶, K. Hamano¹⁶⁸, A. Hamilton^{146a}, G.N. Hamity¹⁴⁰, P.G. Hamnett⁴³, L. Han^{34b}, K. Hanagaki^{68,q}, K. Hanawa¹⁵⁶, M. Hance¹³⁸, B. Haney¹²³, P. Hanke^{59a}, R. Hanna¹³⁷, J.B. Hansen³⁷, J.D. Hansen³⁷, M.C. Hansen²², P.H. Hansen³⁷, K. Hara¹⁶¹, A.S. Hard¹⁷², T. Harenberg¹⁷⁴, F. Hariri¹¹⁸, S. Harkusha⁹⁴, R.D. Harrington⁴⁷, P.F. Harrison¹⁶⁹, F. Hartjes¹⁰⁸, M. Hasegawa⁶⁹, Y. Hasegawa¹⁴¹, A. Hasib¹¹⁴, S. Hassani¹³⁷, S. Haug¹⁷, R. Hauser⁹², L. Hauswald⁴⁵, M. Havranek¹²⁸, C.M. Hawkes¹⁸, R.J. Hawkins³¹, A.D. Hawkins⁸³, T. Hayashi¹⁶¹, D. Hayden⁹², C.P. Hays¹²¹, J.M. Hays⁷⁸, H.S. Hayward⁷⁶, S.J. Haywood¹³², S.J. Head¹⁸, T. Heck⁸⁵, V. Hedberg⁸³, L. Heelan⁸, S. Heim¹²³, T. Heim¹⁵, B. Heinemann¹⁵, J.J. Heinrich¹⁰¹, L. Heinrich¹¹¹, C. Heinz⁵³, J. Hejbal¹²⁸, L. Helary²³, S. Hellman^{147a,147b}, C. Helsens³¹, J. Henderson¹²¹, R.C.W. Henderson⁷⁴, Y. Heng¹⁷², S. Henkelmann¹⁶⁷, A.M. Henriques Correia³¹, S. Henrot-Versille¹¹⁸, G.H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁶, G. Herten⁴⁹, R. Hertenberger¹⁰¹, L. Hervas³¹, G.G. Hesketh⁸⁰, N.P. Hessey¹⁰⁸, J.W. Hetherly⁴¹, R. Hickling⁷⁸, E. Higón-Rodríguez¹⁶⁶, E. Hill¹⁶⁸, J.C. Hill²⁹, K.H. Hiller⁴³, S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²³, R.R. Hinman¹⁵, M. Hirose¹⁵⁸, D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁹, N. Hod¹⁰⁸, M.C. Hodgkinson¹⁴⁰, P. Hodgson¹⁴⁰, A. Hoecker³¹, M.R. Hoferkamp¹⁰⁶, F. Hoenig¹⁰¹, M. Hohlfeld⁸⁵, D. Hohn²², T.R. Holmes¹⁵, M. Homann⁴⁴, T.M. Hong¹²⁶, B.H. Hooberman¹⁶⁵, W.H. Hopkins¹¹⁷, Y. Horii¹⁰⁴, A.J. Horton¹⁴³, J.-Y. Hostachy⁵⁶, S. Hou¹⁵², A. Hoummada^{136a}, J. Howard¹²¹, J. Howarth⁴³, M. Hrabovsky¹¹⁶, I. Hristova¹⁶, J. Hrivnac¹¹⁸, T. Hryn'ova⁵, A. Hrynevich⁹⁵, C. Hsu^{146c}, P.J. Hsu^{152,r}, S.-C. Hsu¹³⁹, D. Hu³⁶, Q. Hu^{34b}, Y. Huang⁴³, Z. Hubacek¹²⁹, F. Hubaut⁸⁷, F. Huegging²², T.B. Huffman¹²¹, E.W. Hughes³⁶, G. Hughes⁷⁴, M. Huhtinen³¹, T.A. Hülsing⁸⁵, N. Huseynov^{67,b}, J. Huston⁹², J. Huth⁵⁸, G. Iacobucci⁵⁰, G. Iakovidis²⁶, I. Ibragimov¹⁴², L. Iconomidou-Fayard¹¹⁸, E. Ideal¹⁷⁵, Z. Idrissi^{136e}, P. Iengo³¹, O. Igonkina¹⁰⁸, T. Iizawa¹⁷⁰, Y. Ikegami⁶⁸, M. Ikeno⁶⁸, Y. Ilchenko^{32,s}, D. Iliadis¹⁵⁵, N. Ilic¹⁴⁴, T. Ince¹⁰², G. Introzzi^{122a,122b}, P. Ioannou^{9,*}, M. Iodice^{135a}, K. Iordanidou³⁶, V. Ippolito⁵⁸, A. Irls Quiles¹⁶⁶, C. Isaksson¹⁶⁴, M. Ishino⁷⁰, M. Ishitsuka¹⁵⁸, R. Ishmukhametov¹¹², C. Issever¹²¹, S. Istin^{19a}, J.M. Iturbe Ponce⁸⁶, R. Iuppa^{134a,134b}, J. Ivarsson⁸³, W. Iwanski⁴⁰, H. Iwasaki⁶⁸, J.M. Izen⁴², V. Izzo^{105a}, S. Jabbar³, B. Jackson¹²³, M. Jackson⁷⁶, P. Jackson¹, V. Jain², K.B. Jakobi⁸⁵, K. Jakobs⁴⁹, S. Jakobsen³¹, T. Jakoubek¹²⁸, D.O. Jamin¹¹⁵, D.K. Jana⁸¹, E. Jansen⁸⁰, R. Jansky⁶³, J. Janssen²², M. Janus⁵⁵, G. Jarlskog⁸³, N. Javadov^{67,b}, T. Javůrek⁴⁹, F. Jeanneau¹³⁷, L. Jeanty¹⁵, J. Jejelava^{52a,t}, G.-Y. Jeng¹⁵¹, D. Jennens⁹⁰, P. Jenni^{49,u}, J. Jentzsch⁴⁴, C. Jeske¹⁶⁹, S. Jézéquel⁵, H. Ji¹⁷², J. Jia¹⁴⁹, H. Jiang⁶⁵, Y. Jiang^{34b}, S. Jiggins⁸⁰, J. Jimenez Pena¹⁶⁶, S. Jin^{34a}, A. Jinaru^{27b}, O. Jinnouchi¹⁵⁸, P. Johansson¹⁴⁰,

K.A. Johns⁷, W.J. Johnson¹³⁹, K. Jon-And^{147a,147b}, G. Jones¹⁶⁹, R.W.L. Jones⁷⁴, S. Jones⁷, T.J. Jones⁷⁶, J. Jongmanns^{59a}, P.M. Jorge^{127a,127b}, J. Jovicevic^{160a}, X. Ju¹⁷², A. Juste Rozas^{12,p}, M.K. Köhler¹⁷¹, M. Kaci¹⁶⁶, A. Kaczmarska⁴⁰, M. Kado¹¹⁸, H. Kagan¹¹², M. Kagan¹⁴⁴, S.J. Kahn⁸⁷, E. Kajomovitz⁴⁶, C.W. Kalderon¹²¹, A. Kaluza⁸⁵, S. Kama⁴¹, A. Kamenshchikov¹³¹, N. Kanaya¹⁵⁶, S. Kaneti²⁹, V.A. Kantserov⁹⁹, J. Kanzaki⁶⁸, B. Kaplan¹¹¹, L.S. Kaplan¹⁷², A. Kapliy³², D. Kar^{146c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis^{10,108}, M.J. Kareem⁵⁵, E. Karentzos¹⁰, M. Karnevskiy⁸⁵, S.N. Karpov⁶⁷, Z.M. Karpova⁶⁷, K. Karthik¹¹¹, V. Kartvelishvili⁷⁴, A.N. Karyukhin¹³¹, K. Kasahara¹⁶¹, L. Kashif¹⁷², R.D. Kass¹¹², A. Kastanas¹⁴, Y. Kataoka¹⁵⁶, C. Kato¹⁵⁶, A. Katre⁵⁰, J. Katzy⁴³, K. Kawade¹⁰⁴, K. Kawagoe⁷², T. Kawamoto¹⁵⁶, G. Kawamura⁵⁵, S. Kazama¹⁵⁶, V.F. Kazanin^{110,c}, R. Keeler¹⁶⁸, R. Kehoe⁴¹, J.S. Keller⁴³, J.J. Kempster⁷⁹, H. Keoshkerian⁸⁶, O. Kepka¹²⁸, B.P. Kerševan⁷⁷, S. Kersten¹⁷⁴, R.A. Keyes⁸⁹, F. Khalil-zada¹¹, H. Khandanyan^{147a,147b}, A. Khanov¹¹⁵, A.G. Kharlamov^{110,c}, T.J. Khoo²⁹, V. Khovanskiy⁹⁸, E. Khramov⁶⁷, J. Khubua^{52b,v}, S. Kido⁶⁹, H.Y. Kim⁸, S.H. Kim¹⁶¹, Y.K. Kim³², N. Kimura¹⁵⁵, O.M. Kind¹⁶, B.T. King⁷⁶, M. King¹⁶⁶, S.B. King¹⁶⁷, J. Kirk¹³², A.E. Kiryunin¹⁰², T. Kishimoto⁶⁹, D. Kisieleska^{39a}, F. Kiss⁴⁹, K. Kiuchi¹⁶¹, O. Kivernyk¹³⁷, E. Kladiva^{145b}, M.H. Klein³⁶, M. Klein⁷⁶, U. Klein⁷⁶, K. Kleinknecht⁸⁵, P. Klimek^{147a,147b}, A. Klimentov²⁶, R. Klingenberg⁴⁴, J.A. Klinger¹⁴⁰, T. Klioutchnikova³¹, E.-E. Kluge^{59a}, P. Kluit¹⁰⁸, S. Kluth¹⁰², J. Knapik⁴⁰, E. Kneringer⁶³, E.B.F.G. Knoop⁸⁷, A. Knue⁵⁴, A. Kobayashi¹⁵⁶, D. Kobayashi¹⁵⁸, T. Kobayashi¹⁵⁶, M. Kobel⁴⁵, M. Kocian¹⁴⁴, P. Kodys¹³⁰, T. Koffas³⁰, E. Koffeman¹⁰⁸, L.A. Kogan¹²¹, S. Kohlmann¹⁷⁴, T. Kohriki⁶⁸, T. Koi¹⁴⁴, H. Kolanoski¹⁶, M. Kolb^{59b}, I. Koletsou⁵, A.A. Komar^{97,*}, Y. Komori¹⁵⁶, T. Kondo⁶⁸, N. Kondrashova⁴³, K. Köneke⁴⁹, A.C. König¹⁰⁷, T. Kono^{68,w}, R. Konoplich^{111,x}, N. Konstantinidis⁸⁰, R. Kopeliansky⁶², S. Koperny^{39a}, L. Köpke⁸⁵, A.K. Kopp⁴⁹, K. Korcyl⁴⁰, K. Kordas¹⁵⁵, A. Korn⁸⁰, A.A. Korol^{110,c}, I. Korolkov¹², E.V. Korolkova¹⁴⁰, O. Kortner¹⁰², S. Kortner¹⁰², T. Kosek¹³⁰, V.V. Kostyukhin²², V.M. Kotov⁶⁷, A. Kotwal⁴⁶, A. Kourkouveli-Charalampidi¹⁵⁵, C. Kourkouvelis⁹, V. Kouskoura²⁶, A. Koutsman^{160a}, R. Kowalewski¹⁶⁸, T.Z. Kowalski^{39a}, W. Kozanecki¹³⁷, A.S. Kozhin¹³¹, V.A. Kramarenko¹⁰⁰, G. Kramberger⁷⁷, D. Krasnopevtsev⁹⁹, M.W. Krasny⁸², A. Krasznahorkay³¹, J.K. Kraus²², A. Kravchenko²⁶, M. Kretz^{59c}, J. Kretzschmar⁷⁶, K. Kreutzfeldt⁵³, P. Krieger¹⁵⁹, K. Krizka³², K. Kroeninger⁴⁴, H. Kroha¹⁰², J. Kroll¹²³, J. Kroseberg²², J. Krstic¹³, U. Kruchonak⁶⁷, H. Krüger²², N. Krumnack⁶⁵, A. Kruse¹⁷², M.C. Kruse⁴⁶, M. Kruskal²³, T. Kubota⁹⁰, H. Kucuk⁸⁰, S. Kuday^{4b}, J.T. Kuechler¹⁷⁴, S. Kuehn⁴⁹, A. Kugel^{59c}, F. Kuger¹⁷³, A. Kuhl¹³⁸, T. Kuhl⁴³, V. Kukhtin⁶⁷, R. Kukla¹³⁷, Y. Kulchitsky⁹⁴, S. Kuleshov^{33b}, M. Kuna^{133a,133b}, T. Kunigo⁷⁰, A. Kupco¹²⁸, H. Kurashige⁶⁹, Y.A. Kurochkin⁹⁴, V. Kus¹²⁸, E.S. Kuwertz¹⁶⁸, M. Kuze¹⁵⁸, J. Kvita¹¹⁶, T. Kwan¹⁶⁸, D. Kyriazopoulos¹⁴⁰, A. La Rosa¹⁰², J.L. La Rosa Navarro^{25d}, L. La Rotonda^{38a,38b}, C. Lacasta¹⁶⁶, F. Lacava^{133a,133b}, J. Lacey³⁰, H. Lacker¹⁶, D. Lacour⁸², V.R. Lacuesta¹⁶⁶, E. Ladygin⁶⁷, R. Lafaye⁵, B. Laforge⁸², T. Lagouri¹⁷⁵, S. Lai⁵⁵, S. Lammers⁶², C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁴⁹, M.P.J. Landon⁷⁸, V.S. Lang^{59a}, J.C. Lange¹², A.J. Lankford⁶⁶, F. Lanni²⁶, K. Lantzsch²², A. Lanza^{122a}, S. Laplace⁸², C. Lapoire³¹, J.F. Laporte¹³⁷, T. Lari^{93a}, F. Lasagni Manghi^{21a,21b}, M. Lassnig³¹, P. Laurelli⁴⁸, W. Lavrijsen¹⁵, A.T. Law¹³⁸, P. Laycock⁷⁶, T. Lazovich⁵⁸, O. Le Dortz⁸², E. Le Guirriec⁸⁷, E. Le Menedeu¹², M. LeBlanc¹⁶⁸, T. LeCompte⁶, F. Ledroit-Guillon⁵⁶, C.A. Lee²⁶, S.C. Lee¹⁵², L. Lee¹, G. Lefebvre⁸², M. Lefebvre¹⁶⁸, F. Legger¹⁰¹, C. Leggett¹⁵, A. Lehan⁷⁶, G. Lehmann Miotto³¹, X. Lei⁷, W.A. Leight³⁰, A. Leisos^{155,y}, A.G. Leister¹⁷⁵, M.A.L. Leite^{25d}, R. Leitner¹³⁰, D. Lellouch¹⁷¹, B. Lemmer⁵⁵, K.J.C. Leney⁸⁰, T. Lenz²², B. Lenzi³¹, R. Leone⁷, S. Leone^{125a,125b}, C. Leonidopoulos⁴⁷, S. Leontsinis¹⁰, C. Leroy⁹⁶, C.G. Lester²⁹, M. Levchenko¹²⁴, J. Levêque⁵, D. Levin⁹¹, L.J. Levinson¹⁷¹, M. Levy¹⁸, A.M. Leyko²², M. Leyton⁴², B. Li^{34b,z}, H. Li¹⁴⁹, H.L. Li³², L. Li⁴⁶, L. Li^{34e}, Q. Li^{34a}, S. Li⁴⁶, X. Li⁸⁶, Y. Li¹⁴², Z. Liang¹³⁸, H. Liao³⁵, B. Liberti^{134a}, A. Liblong¹⁵⁹, P. Lichard³¹, K. Lie¹⁶⁵, J. Liebal²², W. Liebig¹⁴, C. Limbach²², A. Limosani¹⁵¹, S.C. Lin^{152,aa}, T.H. Lin⁸⁵, B.E. Lindquist¹⁴⁹, E. Lipeles¹²³, A. Lipniacka¹⁴, M. Lisovsky^{59b}, T.M. Liss¹⁶⁵, D. Lissauer²⁶, A. Lister¹⁶⁷, A.M. Litke¹³⁸, B. Liu^{152,ab}, D. Liu¹⁵², H. Liu⁹¹, H. Liu²⁶, J. Liu⁸⁷, J.B. Liu^{34b}, K. Liu⁸⁷, L. Liu¹⁶⁵, M. Liu⁴⁶, M. Liu^{34b}, Y.L. Liu^{34b}, Y. Liu^{34b}, M. Livan^{122a,122b}, A. Lleres⁵⁶, J. Llorente Merino⁸⁴, S.L. Lloyd⁷⁸, F. Lo Sterzo¹⁵², E. Lobodzinska⁴³, P. Loch⁷, W.S. Lockman¹³⁸, F.K. Loebinger⁸⁶, A.E. Loevschall-Jensen³⁷, K.M. Loew²⁴, A. Loginov¹⁷⁵, T. Lohse¹⁶, K. Lohwasser⁴³, M. Lokajicek¹²⁸, B.A. Long²³, J.D. Long¹⁶⁵, R.E. Long⁷⁴, L. Longo^{75a,75b}, K.A. Looper¹¹², L. Lopes^{127a}, D. Lopez Mateos⁵⁸, B. Lopez Paredes¹⁴⁰, I. Lopez Paz¹², A. Lopez Solis⁸², J. Lorenz¹⁰¹, N. Lorenzo Martinez⁶², M. Losada²⁰, P.J. Lösel¹⁰¹, X. Lou^{34a}, A. Lounis¹¹⁸, J. Love⁶, P.A. Love⁷⁴,

H. Lu^{61a}, N. Lu⁹¹, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁶, C. Luedtke⁴⁹, F. Luehring⁶², W. Lukas⁶³, L. Luminari^{133a}, O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸, D. Lynn²⁶, R. Lysak¹²⁸, E. Lytken⁸³, H. Ma²⁶, L.L. Ma^{34d}, G. Maccarrone⁴⁸, A. Macchiolo¹⁰², C.M. Macdonald¹⁴⁰, B. Maček⁷⁷, J. Machado Miguens^{123,127b}, D. Madaffari⁸⁷, R. Madar³⁵, H.J. Maddocks¹⁶⁴, W.F. Mader⁴⁵, A. Madsen⁴³, J. Maeda⁶⁹, S. Maeland¹⁴, T. Maeno²⁶, A. Maevskiy¹⁰⁰, E. Magradze⁵⁵, J. Mahlstedt¹⁰⁸, C. Maiani¹¹⁸, C. Maidantchik^{25a}, A.A. Maier¹⁰², T. Maier¹⁰¹, A. Maio^{127a,127b,127d}, S. Majewski¹¹⁷, Y. Makida⁶⁸, N. Makovec¹¹⁸, B. Malaescu⁸², Pa. Malecki⁴⁰, V.P. Maleev¹²⁴, F. Malek⁵⁶, U. Mallik⁶⁴, D. Malon⁶, C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹¹⁰, S. Malyukov³¹, J. Mamuzic⁴³, G. Mancini⁴⁸, B. Mandelli³¹, L. Mandelli^{93a}, I. Mandić⁷⁷, J. Maneira^{127a,127b}, L. Manhaes de Andrade Filho^{25b}, J. Manjarres Ramos^{160b}, A. Mann¹⁰¹, B. Mansoulie¹³⁷, R. Mantifel⁸⁹, M. Mantoani⁵⁵, S. Manzoni^{93a,93b}, L. Mapelli³¹, G. Marceca²⁸, L. March⁵⁰, G. Marchiori⁸², M. Marcisovsky¹²⁸, M. Marjanovic¹³, D.E. Marley⁹¹, F. Marroquim^{25a}, S.P. Marsden⁸⁶, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁶, B. Martin⁹², T.A. Martin¹⁶⁹, V.J. Martin⁴⁷, B. Martin dit Latour¹⁴, M. Martinez^{12,p}, S. Martin-Haugh¹³², V.S. Martoiu^{27b}, A.C. Martyniuk⁸⁰, M. Marx¹³⁹, F. Marzano^{133a}, A. Marzin³¹, L. Masetti⁸⁵, T. Mashimo¹⁵⁶, R. Mashinistov⁹⁷, J. Masik⁸⁶, A.L. Maslennikov^{110,c}, I. Massa^{21a,21b}, L. Massa^{21a,21b}, P. Mastrandrea⁵, A. Mastroberardino^{38a,38b}, T. Masubuchi¹⁵⁶, P. Mättig¹⁷⁴, J. Mattmann⁸⁵, J. Maurer^{27b}, S.J. Maxfield⁷⁶, D.A. Maximov^{110,c}, R. Mazini¹⁵², S.M. Mazza^{93a,93b}, N.C. Mc Fadden¹⁰⁶, G. Mc Goldrick¹⁵⁹, S.P. Mc Kee⁹¹, A. McCarn⁹¹, R.L. McCarthy¹⁴⁹, T.G. McCarthy³⁰, K.W. McFarlane^{57,*}, J.A. Mcfayden⁸⁰, G. Mchedlidze⁵⁵, S.J. McMahon¹³², R.A. McPherson^{168,l}, M. Medinnis⁴³, S. Meehan¹³⁹, S. Mehlhase¹⁰¹, A. Mehta⁷⁶, K. Meier^{59a}, C. Meineck¹⁰¹, B. Meirose⁴², B.R. Mellado Garcia^{146c}, F. Meloni¹⁷, A. Mengarelli^{21a,21b}, S. Menke¹⁰², E. Meoni¹⁶², K.M. Mercurio⁵⁸, S. Mergelmeyer¹⁶, P. Mermod⁵⁰, L. Merola^{105a,105b}, C. Meroni^{93a}, F.S. Merritt³², A. Messina^{133a,133b}, J. Metcalfe⁶, A.S. Mete⁶⁶, C. Meyer⁸⁵, C. Meyer¹²³, J-P. Meyer¹³⁷, J. Meyer¹⁰⁸, H. Meyer Zu Theenhausen^{59a}, R.P. Middleton¹³², S. Miglioranza^{163a,163c}, L. Mijović²², G. Mikenberg¹⁷¹, M. Mikesikova¹²⁸, M. Mikuž⁷⁷, M. Milesi⁹⁰, A. Milic³¹, D.W. Miller³², C. Mills⁴⁷, A. Milov¹⁷¹, D.A. Milstead^{147a,147b}, A.A. Minaenko¹³¹, Y. Minami¹⁵⁶, I.A. Minashvili⁶⁷, A.I. Mincer¹¹¹, B. Mindur^{39a}, M. Mineev⁶⁷, Y. Ming¹⁷², L.M. Mir¹², K.P. Mistry¹²³, T. Mitani¹⁷⁰, J. Mitrevski¹⁰¹, V.A. Mitsou¹⁶⁶, A. Miucci⁵⁰, P.S. Miyagawa¹⁴⁰, J.U. Mjörnmark⁸³, T. Moa^{147a,147b}, K. Mochizuki⁸⁷, S. Mohapatra³⁶, W. Mohr⁴⁹, S. Molander^{147a,147b}, R. Moles-Valls²², R. Monden⁷⁰, M.C. Mondragon⁹², K. Mönig⁴³, J. Monk³⁷, E. Monnier⁸⁷, A. Montalbano¹⁴⁹, J. Montejo Berlingen³¹, F. Monticelli⁷³, S. Monzani^{93a,93b}, R.W. Moore³, N. Morange¹¹⁸, D. Moreno²⁰, M. Moreno Llácer⁵⁵, P. Morettini^{51a}, D. Mori¹⁴³, T. Mori¹⁵⁶, M. Morii⁵⁸, M. Morinaga¹⁵⁶, V. Morisbak¹²⁰, S. Moritz⁸⁵, A.K. Morley¹⁵¹, G. Mornacchi³¹, J.D. Morris⁷⁸, S.S. Mortensen³⁷, L. Morvaj¹⁴⁹, M. Mosidze^{52b}, J. Moss¹⁴⁴, K. Motohashi¹⁵⁸, R. Mount¹⁴⁴, E. Mountricha²⁶, S.V. Mouraviev^{97,*}, E.J.W. Moyse⁸⁸, S. Muanza⁸⁷, R.D. Mudd¹⁸, F. Mueller¹⁰², J. Mueller¹²⁶, R.S.P. Mueller¹⁰¹, T. Mueller²⁹, D. Muenstermann⁷⁴, P. Mullen⁵⁴, G.A. Mullier¹⁷, F.J. Munoz Sanchez⁸⁶, J.A. Murillo Quijada¹⁸, W.J. Murray^{169,132}, H. Musheghyan⁵⁵, A.G. Myagkov^{131,ac}, M. Myska¹²⁹, B.P. Nachman¹⁴⁴, O. Nackenhorst⁵⁰, J. Nadal⁵⁵, K. Nagai¹²¹, R. Nagai^{68,w}, Y. Nagai⁸⁷, K. Nagano⁶⁸, Y. Nagasaka⁶⁰, K. Nagata¹⁶¹, M. Nagel¹⁰², E. Nagy⁸⁷, A.M. Nairz³¹, Y. Nakahama³¹, K. Nakamura⁶⁸, T. Nakamura¹⁵⁶, I. Nakano¹¹³, H. Namasivayam⁴², R.F. Naranjo Garcia⁴³, R. Narayan³², D.I. Narrias Villar^{59a}, I. Naryshkin¹²⁴, T. Naumann⁴³, G. Navarro²⁰, R. Nayyar⁷, H.A. Neal⁹¹, P.Yu. Nechaeva⁹⁷, T.J. Neep⁸⁶, P.D. Nef¹⁴⁴, A. Negri^{122a,122b}, M. Negrini^{21a}, S. Nektarijevic¹⁰⁷, C. Nellist¹¹⁸, A. Nelson⁶⁶, S. Nemecek¹²⁸, P. Nemethy¹¹¹, A.A. Nepomuceno^{25a}, M. Nessi^{31,ad}, M.S. Neubauer¹⁶⁵, M. Neumann¹⁷⁴, R.M. Neves¹¹¹, P. Nevski²⁶, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹²¹, R. Nicolaïdou¹³⁷, B. Nicquevert³¹, J. Nielsen¹³⁸, A. Nikiforov¹⁶, V. Nikolaenko^{131,ac}, I. Nikolic-Audit⁸², K. Nikolopoulos¹⁸, J.K. Nilsen¹²⁰, P. Nilsson²⁶, Y. Ninomiya¹⁵⁶, A. Nisati^{133a}, R. Nisius¹⁰², T. Nobe¹⁵⁶, L. Nodulman⁶, M. Nomachi¹¹⁹, I. Nomidis³⁰, T. Nooney⁷⁸, S. Norberg¹¹⁴, M. Nordberg³¹, O. Novgorodova⁴⁵, S. Nowak¹⁰², M. Nozaki⁶⁸, L. Nozka¹¹⁶, K. Ntekas¹⁰, E. Nurse⁸⁰, F. Nuti⁹⁰, F. O'grady⁷, D.C. O'Neil¹⁴³, V. O'Shea⁵⁴, F.G. Oakham^{30,d}, H. Oberlack¹⁰², T. Obermann²², J. Ocariz⁸², A. Ochi⁶⁹, I. Ochoa³⁶, J.P. Ochoa-Ricoux^{33a}, S. Oda⁷², S. Odaka⁶⁸, H. Ogren⁶², A. Oh⁸⁶, S.H. Oh⁴⁶, C.C. Ohm¹⁵, H. Ohman¹⁶⁴, H. Oide³¹, H. Okawa¹⁶¹, Y. Okumura³², T. Okuyama⁶⁸, A. Olariu^{27b}, L.F. Oleiro Seabra^{127a}, S.A. Olivares Pino⁴⁷, D. Oliveira Damazio²⁶, A. Olszewski⁴⁰, J. Olszowska⁴⁰, A. Onofre^{127a,127e}, K. Onogi¹⁰⁴, P.U.E. Onyisi^{32,s}, C.J. Oram^{160a}, M.J. Oreglia³²,

Y. Oren¹⁵⁴, D. Orestano^{135a,135b}, N. Orlando^{61b}, R.S. Orr¹⁵⁹, B. Osculati^{51a,51b}, R. Ospanov⁸⁶, G. Otero y Garzon²⁸, H. Otono⁷², M. Ouchrif^{136d}, F. Ould-Saada¹²⁰, A. Ouraou¹³⁷, K.P. Oussoren¹⁰⁸, Q. Ouyang^{34a}, A. Ovcharova¹⁵, M. Owen⁵⁴, R.E. Owen¹⁸, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹⁴³, A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁹, S. Pagan Griso¹⁵, F. Paige²⁶, P. Pais⁸⁸, K. Pajchel¹²⁰, G. Palacino^{160b}, S. Palestini³¹, M. Palka^{39b}, D. Pallin³⁵, A. Palma^{127a,127b}, E. St. Panagiotopoulou¹⁰, C.E. Pandini⁸², J.G. Panduro Vazquez⁷⁹, P. Pani^{147a,147b}, S. Panitkin²⁶, D. Pantea^{27b}, L. Paolozzi⁵⁰, Th.D. Papadopoulou¹⁰, K. Papageorgiou¹⁵⁵, A. Paramonov⁶, D. Paredes Hernandez¹⁷⁵, M.A. Parker²⁹, K.A. Parker¹⁴⁰, F. Parodi^{51a,51b}, J.A. Parsons³⁶, U. Parzefall⁴⁹, V. Pascuzzi¹⁵⁹, E. Pasqualucci^{133a}, S. Passaggio^{51a}, F. Pastore^{135a,135b,*}, Fr. Pastore⁷⁹, G. Pásztor³⁰, S. Pataraiia¹⁷⁴, N.D. Patel¹⁵¹, J.R. Pater⁸⁶, T. Pauly³¹, J. Pearce¹⁶⁸, B. Pearson¹¹⁴, L.E. Pedersen³⁷, M. Pedersen¹²⁰, S. Pedraza Lopez¹⁶⁶, R. Pedro^{127a,127b}, S.V. Peleganchuk^{110,c}, D. Pelikan¹⁶⁴, O. Penc¹²⁸, C. Peng^{34a}, H. Peng^{34b}, J. Penwell⁶², B.S. Peralva^{25b}, D.V. Perepelitsa²⁶, E. Perez Codina^{160a}, L. Perini^{93a,93b}, H. Pernegger³¹, S. Perrella^{105a,105b}, R. Peschke⁴³, V.D. Peshekhonov⁶⁷, K. Peters³¹, R.F.Y. Peters⁸⁶, B.A. Petersen³¹, T.C. Petersen³⁷, E. Petit⁵⁶, A. Petridis¹, C. Petridou¹⁵⁵, P. Petroff¹¹⁸, E. Petrolo^{133a}, F. Petrucci^{135a,135b}, N.E. Pettersson¹⁵⁸, A. Peyaud¹³⁷, R. Pezoa^{33b}, P.W. Phillips¹³², G. Piacquadio¹⁴⁴, E. Pianori¹⁶⁹, A. Picazio⁸⁸, E. Piccaro⁷⁸, M. Piccinini^{21a,21b}, M.A. Pickering¹²¹, R. Piegaia²⁸, J.E. Pilcher³², A.D. Pilkington⁸⁶, A.W.J. Pin⁸⁶, J. Pina^{127a,127b,127d}, M. Pinamonti^{163a,163c,ae}, J.L. Pinfold³, A. Pingel³⁷, S. Pires⁸², H. Pirumov⁴³, M. Pitt¹⁷¹, L. Plazak^{145a}, M.-A. Pleier²⁶, V. Pleskot⁸⁵, E. Plotnikova⁶⁷, P. Plucinski^{147a,147b}, D. Pluth⁶⁵, R. Poettgen^{147a,147b}, L. Poggioli¹¹⁸, D. Pohl²², G. Polesello^{122a}, A. Poley⁴³, A. Policicchio^{38a,38b}, R. Polifka¹⁵⁹, A. Polini^{21a}, C.S. Pollard⁵⁴, V. Polychronakos²⁶, K. Pommès³¹, L. Pontecorvo^{133a}, B.G. Pope⁹², G.A. Popeneciu^{27c}, D.S. Popovic¹³, A. Poppleton³¹, S. Pospisil¹²⁹, K. Potamianos¹⁵, I.N. Potrap⁶⁷, C.J. Potter²⁹, C.T. Potter¹¹⁷, G. Poulard³¹, J. Poveda³¹, V. Pozdnyakov⁶⁷, M.E. Pozo Astigarraga³¹, P. Pralavorio⁸⁷, A. Pranko¹⁵, S. Prell⁶⁵, D. Price⁸⁶, L.E. Price⁶, M. Primavera^{75a}, S. Prince⁸⁹, M. Proissl⁴⁷, K. Prokofiev^{61c}, F. Prokoshin^{33b}, S. Protopopescu²⁶, J. Proudfoot⁶, M. Przybycien^{39a}, D. Puddu^{135a,135b}, D. Puldon¹⁴⁹, M. Purohit^{26,af}, P. Puzo¹¹⁸, J. Qian⁹¹, G. Qin⁵⁴, Y. Qin⁸⁶, A. Quadt⁵⁵, D.R. Quarrie¹⁵, W.B. Quayle^{163a,163b}, M. Queitsch-Maitland⁸⁶, D. Quilty⁵⁴, S. Raddum¹²⁰, V. Radeka²⁶, V. Radescu⁴³, S.K. Radhakrishnan¹⁴⁹, P. Radloff¹¹⁷, P. Rados⁹⁰, F. Ragusa^{93a,93b}, G. Rahal¹⁷⁷, S. Rajagopalan²⁶, M. Rammensee³¹, C. Rangel-Smith¹⁶⁴, F. Rauscher¹⁰¹, S. Rave⁸⁵, T. Ravenscroft⁵⁴, M. Raymond³¹, A.L. Read¹²⁰, N.P. Readioff⁷⁶, D.M. Rebuzzi^{122a,122b}, A. Redelbach¹⁷³, G. Redlinger²⁶, R. Reece¹³⁸, K. Reeves⁴², L. Rehnisch¹⁶, J. Reichert¹²³, H. Reisin²⁸, C. Rembser³¹, H. Ren^{34a}, M. Rescigno^{133a}, S. Resconi^{93a}, O.L. Rezanova^{110,c}, P. Reznicek¹³⁰, R. Rezvani⁹⁶, R. Richter¹⁰², S. Richter⁸⁰, E. Richter-Was^{39b}, O. Ricken²², M. Ridet⁸², P. Rieck¹⁶, C.J. Riegel¹⁷⁴, J. Rieger⁵⁵, O. Rifki¹¹⁴, M. Rijssenbeek¹⁴⁹, A. Rimoldi^{122a,122b}, L. Rinaldi^{21a}, B. Ristić⁵⁰, E. Ritsch³¹, I. Riu¹², F. Rizatdinova¹¹⁵, E. Rizvi⁷⁸, S.H. Robertson^{89,l}, A. Robichaud-Veronneau⁸⁹, D. Robinson²⁹, J.E.M. Robinson⁴³, A. Robson⁵⁴, C. Roda^{125a,125b}, Y. Rodina⁸⁷, A. Rodriguez Perez¹², S. Roe³¹, C.S. Rogan⁵⁸, O. Röhne¹²⁰, A. Romaniouk⁹⁹, M. Romano^{21a,21b}, S.M. Romano Saez³⁵, E. Romero Adam¹⁶⁶, N. Rompotis¹³⁹, M. Ronzani⁴⁹, L. Roos⁸², E. Ros¹⁶⁶, S. Rosati^{133a}, K. Rosbach⁴⁹, P. Rose¹³⁸, O. Rosenthal¹⁴², V. Rossetti^{147a,147b}, E. Rossi^{105a,105b}, L.P. Rossi^{51a}, J.H.N. Rosten²⁹, R. Rosten¹³⁹, M. Rotaru^{27b}, I. Roth¹⁷¹, J. Rothberg¹³⁹, D. Rousseau¹¹⁸, C.R. Royon¹³⁷, A. Rozanov⁸⁷, Y. Rozen¹⁵³, X. Ruan^{146c}, F. Rubbo¹⁴⁴, I. Rubinskiy⁴³, V.I. Rud¹⁰⁰, M.S. Rudolph¹⁵⁹, F. Rühr⁴⁹, A. Ruiz-Martinez³¹, Z. Rurikova⁴⁹, N.A. Rusakovich⁶⁷, A. Ruschke¹⁰¹, H.L. Russell¹³⁹, J.P. Rutherford⁷, N. Ruthmann³¹, Y.F. Ryabov¹²⁴, M. Rybar¹⁶⁵, G. Rybkin¹¹⁸, N.C. Ryder¹²¹, S. Ryu⁶, A. Ryzhov¹³¹, A.F. Saavedra¹⁵¹, G. Sabato¹⁰⁸, S. Sacerdoti²⁸, H.F.-W. Sadrozinski¹³⁸, R. Sadykov⁶⁷, F. Safai Tehrani^{133a}, P. Saha¹⁰⁹, M. Sahinsoy^{59a}, M. Saimpert¹³⁷, T. Saito¹⁵⁶, H. Sakamoto¹⁵⁶, Y. Sakurai¹⁷⁰, G. Salamanna^{135a,135b}, A. Salamon^{134a}, J.E. Salazar Loyola^{33b}, D. Salek¹⁰⁸, P.H. Sales De Bruin¹³⁹, D. Salihagic¹⁰², A. Salnikov¹⁴⁴, J. Salt¹⁶⁶, D. Salvatore^{38a,38b}, F. Salvatore¹⁵⁰, A. Salvucci^{61a}, A. Salzburger³¹, D. Sammel⁴⁹, D. Sampsonidis¹⁵⁵, A. Sanchez^{105a,105b}, J. Sánchez¹⁶⁶, V. Sanchez Martinez¹⁶⁶, H. Sandaker¹²⁰, R.L. Sandbach⁷⁸, H.G. Sander⁸⁵, M.P. Sanders¹⁰¹, M. Sandhoff¹⁷⁴, C. Sandoval²⁰, R. Sandstroem¹⁰², D.P.C. Sankey¹³², M. Sannino^{51a,51b}, A. Sansoni⁴⁸, C. Santoni³⁵, R. Santonico^{134a,134b}, H. Santos^{127a}, I. Santoyo Castillo¹⁵⁰, K. Sapp¹²⁶, A. Saprionov⁶⁷, J.G. Saraiva^{127a,127d}, B. Sarrazin²², O. Sasaki⁶⁸, Y. Sasaki¹⁵⁶, K. Sato¹⁶¹, G. Sauvage^{5,*}, E. Sauvan⁵, G. Savage⁷⁹, P. Savard^{159,d}, C. Sawyer¹³², L. Sawyer^{81,o}, J. Saxon³²,

C. Sbarra ^{21a}, A. Sbrizzi ^{21a,21b}, T. Scanlon ⁸⁰, D.A. Scannicchio ⁶⁶, M. Scarcella ¹⁵¹, V. Scarfone ^{38a,38b}, J. Schaarschmidt ¹⁷¹, P. Schacht ¹⁰², D. Schaefer ³¹, R. Schaefer ⁴³, J. Schaeffer ⁸⁵, S. Schaepe ²², S. Schaetzel ^{59b}, U. Schäfer ⁸⁵, A.C. Schaffer ¹¹⁸, D. Schaile ¹⁰¹, R.D. Schamberger ¹⁴⁹, V. Scharf ^{59a}, V.A. Schegelsky ¹²⁴, D. Scheirich ¹³⁰, M. Schernau ⁶⁶, C. Schiavi ^{51a,51b}, C. Schillo ⁴⁹, M. Schioppa ^{38a,38b}, S. Schlenker ³¹, K. Schmieden ³¹, C. Schmitt ⁸⁵, S. Schmitt ^{59b}, S. Schmitt ⁴³, S. Schmitz ⁸⁵, B. Schneider ^{160a}, Y.J. Schnellbach ⁷⁶, U. Schnoor ⁴⁹, L. Schoeffel ¹³⁷, A. Schoening ^{59b}, B.D. Schoenrock ⁹², E. Schopf ²², A.L.S. Schorlemmer ⁵⁵, M. Schott ⁸⁵, D. Schouten ^{160a}, J. Schovancova ⁸, S. Schramm ⁵⁰, M. Schreyer ¹⁷³, N. Schuh ⁸⁵, M.J. Schultens ²², H.-C. Schultz-Coulon ^{59a}, H. Schulz ¹⁶, M. Schumacher ⁴⁹, B.A. Schumm ¹³⁸, Ph. Schune ¹³⁷, C. Schwanenberger ⁸⁶, A. Schwartzman ¹⁴⁴, T.A. Schwarz ⁹¹, Ph. Schwegler ¹⁰², H. Schweiger ⁸⁶, Ph. Schwemling ¹³⁷, R. Schwienhorst ⁹², J. Schwindling ¹³⁷, T. Schwindt ²², G. Sciolla ²⁴, F. Scuri ^{125a,125b}, F. Scutti ⁹⁰, J. Searcy ⁹¹, P. Seema ²², S.C. Seidel ¹⁰⁶, A. Seiden ¹³⁸, F. Seifert ¹²⁹, J.M. Seixas ^{25a}, G. Sekhniaidze ^{105a}, K. Sekhon ⁹¹, S.J. Sekula ⁴¹, D.M. Seliverstov ^{124,*}, N. Semprini-Cesari ^{21a,21b}, C. Serfon ³¹, L. Serin ¹¹⁸, L. Serkin ^{163a,163b}, M. Sessa ^{135a,135b}, R. Seuster ^{160a}, H. Severini ¹¹⁴, T. Sfiligoi ⁷⁷, F. Sforza ³¹, A. Sfyrla ⁵⁰, E. Shabalina ⁵⁵, N.W. Shaikh ^{147a,147b}, L.Y. Shan ^{34a}, R. Shang ¹⁶⁵, J.T. Shank ²³, M. Shapiro ¹⁵, P.B. Shatalov ⁹⁸, K. Shaw ^{163a,163b}, S.M. Shaw ⁸⁶, A. Shcherbakova ^{147a,147b}, C.Y. Shehu ¹⁵⁰, P. Sherwood ⁸⁰, L. Shi ^{152,ag}, S. Shimizu ⁶⁹, C.O. Shimmin ⁶⁶, M. Shimojima ¹⁰³, M. Shiyakova ^{67,ah}, A. Shmeleva ⁹⁷, D. Shoaleh Saadi ⁹⁶, M.J. Shochet ³², S. Shojaii ^{93a,93b}, S. Shrestha ¹¹², E. Shulga ⁹⁹, M.A. Shupe ⁷, P. Sicho ¹²⁸, P.E. Sidebo ¹⁴⁸, O. Sidiropoulou ¹⁷³, D. Sidorov ¹¹⁵, A. Sidoti ^{21a,21b}, F. Siegert ⁴⁵, Dj. Sijacki ¹³, J. Silva ^{127a,127d}, S.B. Silverstein ^{147a}, V. Simak ¹²⁹, O. Simard ⁵, Lj. Simic ¹³, S. Simion ¹¹⁸, E. Simioni ⁸⁵, B. Simmons ⁸⁰, D. Simon ³⁵, M. Simon ⁸⁵, P. Sinervo ¹⁵⁹, N.B. Sinev ¹¹⁷, M. Sioli ^{21a,21b}, G. Siragusa ¹⁷³, S.Yu. Sivoklov ¹⁰⁰, J. Sjölin ^{147a,147b}, T.B. Sjursen ¹⁴, M.B. Skinner ⁷⁴, H.P. Skottowe ⁵⁸, P. Skubic ¹¹⁴, M. Slater ¹⁸, T. Slavicek ¹²⁹, M. Slawinska ¹⁰⁸, K. Sliwa ¹⁶², V. Smakhtin ¹⁷¹, B.H. Smart ⁴⁷, L. Smestad ¹⁴, S.Yu. Smirnov ⁹⁹, Y. Smirnov ⁹⁹, L.N. Smirnova ^{100,ai}, O. Smirnova ⁸³, M.N.K. Smith ³⁶, R.W. Smith ³⁶, M. Smizanska ⁷⁴, K. Smolek ¹²⁹, A.A. Snesarev ⁹⁷, G. Snidero ⁷⁸, S. Snyder ²⁶, R. Sobie ^{168,l}, F. Socher ⁴⁵, A. Soffer ¹⁵⁴, D.A. Soh ^{152,ag}, G. Sokhrannyi ⁷⁷, C.A. Solans Sanchez ³¹, M. Solar ¹²⁹, E.Yu. Soldatov ⁹⁹, U. Soldevila ¹⁶⁶, A.A. Solodkov ¹³¹, A. Soloshenko ⁶⁷, O.V. Solovyanov ¹³¹, V. Solovyev ¹²⁴, P. Sommer ⁴⁹, H.Y. Song ^{34b,z}, N. Soni ¹, A. Sood ¹⁵, A. Sopczak ¹²⁹, V. Sopko ¹²⁹, V. Sorin ¹², D. Sosa ^{59b}, C.L. Sotiropoulou ^{125a,125b}, R. Soualah ^{163a,163c}, A.M. Soukharev ^{110,c}, D. South ⁴³, B.C. Sowden ⁷⁹, S. Spagnolo ^{75a,75b}, M. Spalla ^{125a,125b}, M. Spangenberg ¹⁶⁹, F. Spanò ⁷⁹, D. Sperlich ¹⁶, F. Spettel ¹⁰², R. Spighi ^{21a}, G. Spigo ³¹, L.A. Spiller ⁹⁰, M. Spousta ¹³⁰, R.D. St. Denis ^{54,*}, A. Stabile ^{93a}, S. Staerz ³¹, J. Stahlman ¹²³, R. Stamen ^{59a}, S. Stamm ¹⁶, E. Stanecka ⁴⁰, R.W. Stanek ⁶, C. Stanescu ^{135a}, M. Stanescu-Bellu ⁴³, M.M. Stanitzki ⁴³, S. Stapnes ¹²⁰, E.A. Starchenko ¹³¹, G.H. Stark ³², J. Stark ⁵⁶, P. Staroba ¹²⁸, P. Starovoitov ^{59a}, R. Staszewski ⁴⁰, P. Steinberg ²⁶, B. Stelzer ¹⁴³, H.J. Stelzer ³¹, O. Stelzer-Chilton ^{160a}, H. Stenzel ⁵³, G.A. Stewart ⁵⁴, J.A. Stillings ²², M.C. Stockton ⁸⁹, M. Stoebe ⁸⁹, G. Stoicea ^{27b}, P. Stolte ⁵⁵, S. Stonjek ¹⁰², A.R. Stradling ⁸, A. Straessner ⁴⁵, M.E. Stramaglia ¹⁷, J. Strandberg ¹⁴⁸, S. Strandberg ^{147a,147b}, A. Strandlie ¹²⁰, M. Strauss ¹¹⁴, P. Strizenec ^{145b}, R. Ströhmer ¹⁷³, D.M. Strom ¹¹⁷, R. Stroynowski ⁴¹, A. Strubig ¹⁰⁷, S.A. Stucci ¹⁷, B. Stugu ¹⁴, N.A. Styles ⁴³, D. Su ¹⁴⁴, J. Su ¹²⁶, R. Subramaniam ⁸¹, S. Suchek ^{59a}, Y. Sugaya ¹¹⁹, M. Suk ¹²⁹, V.V. Sulin ⁹⁷, S. Sultansoy ^{4c}, T. Sumida ⁷⁰, S. Sun ⁵⁸, X. Sun ^{34a}, J.E. Sundermann ⁴⁹, K. Suruliz ¹⁵⁰, G. Susinno ^{38a,38b}, M.R. Sutton ¹⁵⁰, S. Suzuki ⁶⁸, M. Svatos ¹²⁸, M. Swiatlowski ³², I. Sykora ^{145a}, T. Sykora ¹³⁰, D. Ta ⁴⁹, C. Taccini ^{135a,135b}, K. Tackmann ⁴³, J. Taenzer ¹⁵⁹, A. Taffard ⁶⁶, R. Tahirout ^{160a}, N. Taiblum ¹⁵⁴, H. Takai ²⁶, R. Takashima ⁷¹, H. Takeda ⁶⁹, T. Takeshita ¹⁴¹, Y. Takubo ⁶⁸, M. Talby ⁸⁷, A.A. Talyshev ^{110,c}, J.Y.C. Tam ¹⁷³, K.G. Tan ⁹⁰, J. Tanaka ¹⁵⁶, R. Tanaka ¹¹⁸, S. Tanaka ⁶⁸, B.B. Tannenwald ¹¹², S. Tapia Araya ^{33b}, S. Tapprogge ⁸⁵, S. Tarem ¹⁵³, G.F. Tartarelli ^{93a}, P. Tas ¹³⁰, M. Tasevsky ¹²⁸, T. Tashiro ⁷⁰, E. Tassi ^{38a,38b}, A. Tavares Delgado ^{127a,127b}, Y. Tayalati ^{136d}, A.C. Taylor ¹⁰⁶, G.N. Taylor ⁹⁰, P.T.E. Taylor ⁹⁰, W. Taylor ^{160b}, F.A. Teischinger ³¹, P. Teixeira-Dias ⁷⁹, K.K. Temming ⁴⁹, D. Temple ¹⁴³, H. Ten Kate ³¹, P.K. Teng ¹⁵², J.J. Teoh ¹¹⁹, F. Tepel ¹⁷⁴, S. Terada ⁶⁸, K. Terashi ¹⁵⁶, J. Terron ⁸⁴, S. Terzo ¹⁰², M. Testa ⁴⁸, R.J. Teuscher ^{159,l}, T. Theveneaux-Pelzer ⁸⁷, J.P. Thomas ¹⁸, J. Thomas-Wilsker ⁷⁹, E.N. Thompson ³⁶, P.D. Thompson ¹⁸, R.J. Thompson ⁸⁶, A.S. Thompson ⁵⁴, L.A. Thomsen ¹⁷⁵, E. Thomson ¹²³, M. Thomson ²⁹, M.J. Tibbetts ¹⁵, R.E. Ticse Torres ⁸⁷, V.O. Tikhomirov ^{97,aj}, Yu.A. Tikhonov ^{110,c}, S. Timoshenko ⁹⁹, E. Tiouchichine ⁸⁷, P. Tipton ¹⁷⁵, S. Tisserant ⁸⁷, K. Todome ¹⁵⁸, T. Todorov ^{5,*}, S. Todorova-Nova ¹³⁰, J. Tojo ⁷², S. Tokár ^{145a},

K. Tokushuku⁶⁸, E. Tolley⁵⁸, L. Tomlinson⁸⁶, M. Tomoto¹⁰⁴, L. Tompkins^{144,ak}, K. Toms¹⁰⁶, B. Tong⁵⁸, E. Torrence¹¹⁷, H. Torres¹⁴³, E. Torró Pastor¹³⁹, J. Toth^{87,al}, F. Touchard⁸⁷, D.R. Tovey¹⁴⁰, T. Trefzger¹⁷³, L. Tremblet³¹, A. Tricoli³¹, I.M. Trigger^{160a}, S. Trincaz-Duvold⁸², M.F. Tripiana¹², W. Trischuk¹⁵⁹, B. Trocmé⁵⁶, A. Trofymov⁴³, C. Troncon^{93a}, M. Trottier-McDonald¹⁵, M. Trovatelli¹⁶⁸, L. Truong^{163a,163b}, M. Trzebinski⁴⁰, A. Trzupek⁴⁰, J.C.-L. Tseng¹²¹, P.V. Tsiarshka⁹⁴, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁹, E.G. Tskhadadze^{52a}, K.M. Tsui^{61a}, I.I. Tsukerman⁹⁸, V. Tsulaia¹⁵, S. Tsuno⁶⁸, D. Tsybychev¹⁴⁹, A. Tudorache^{27b}, V. Tudorache^{27b}, A.N. Tuna⁵⁸, S.A. Tupputi^{21a,21b}, S. Turchikhin^{100,ai}, D. Turecek¹²⁹, D. Turgeman¹⁷¹, R. Turra^{93a,93b}, A.J. Turvey⁴¹, P.M. Tuts³⁶, M. Tylmad^{147a,147b}, M. Tyndel¹³², I. Ueda¹⁵⁶, R. Ueno³⁰, M. Ughetto^{147a,147b}, F. Ukegawa¹⁶¹, G. Unal³¹, A. Undrus²⁶, G. Unel⁶⁶, F.C. Ungaro⁹⁰, Y. Unno⁶⁸, C. Unverdorben¹⁰¹, J. Urban^{145b}, P. Urquijo⁹⁰, P. Urrejola⁸⁵, G. Usai⁸, A. Usanova⁶³, L. Vacavant⁸⁷, V. Vacek¹²⁹, B. Vachon⁸⁹, C. Valderanis⁸⁵, N. Valencic¹⁰⁸, S. Valentinetti^{21a,21b}, A. Valero¹⁶⁶, L. Valery¹², S. Valkar¹³⁰, S. Vallecorsa⁵⁰, J.A. Valls Ferrer¹⁶⁶, W. Van Den Wollenberg¹⁰⁸, P.C. Van Der Deijl¹⁰⁸, R. van der Geer¹⁰⁸, H. van der Graaf¹⁰⁸, N. van Eldik¹⁵³, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁸, M.C. van Woerden³¹, M. Vanadia^{133a,133b}, W. Vandelli³¹, R. Vanguri¹²³, A. Vaniachine⁶, G. Vardanyan¹⁷⁶, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁴¹, D. Varouchas⁸², A. Vartapetian⁸, K.E. Varvell¹⁵¹, F. Vazeille³⁵, T. Vazquez Schroeder⁸⁹, J. Veatch⁷, L.M. Veloce¹⁵⁹, F. Veloso^{127a,127c}, S. Veneziano^{133a}, A. Ventura^{75a,75b}, M. Venturi¹⁶⁸, N. Venturi¹⁵⁹, A. Venturini²⁴, V. Vercesi^{122a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁸, J.C. Vermeulen¹⁰⁸, A. Vest^{45,am}, M.C. Vetterli^{143,d}, O. Viazlo⁸³, I. Vichou¹⁶⁵, T. Vickey¹⁴⁰, O.E. Vickey Boeriu¹⁴⁰, G.H.A. Viehhauser¹²¹, S. Viel¹⁵, R. Vigne⁶³, M. Villa^{21a,21b}, M. Villaplana Perez^{93a,93b}, E. Vilucchi⁴⁸, M.G. Vincet³⁰, V.B. Vinogradov⁶⁷, I. Vivarelli¹⁵⁰, S. Vlachos¹⁰, M. Vlasak¹²⁹, M. Vogel¹⁷⁴, P. Vokac¹²⁹, G. Volpi^{125a,125b}, M. Volpi⁹⁰, H. von der Schmitt¹⁰², E. von Toerne²², V. Vorobel¹³⁰, K. Vorobev⁹⁹, M. Vos¹⁶⁶, R. Voss³¹, J.H. Vosseveld⁷⁶, N. Vranjes¹³, M. Vranjes Milosavljevic¹³, V. Vrba¹²⁸, M. Vreeswijk¹⁰⁸, R. Vuillermet³¹, I. Vukotic³², Z. Vykydal¹²⁹, P. Wagner²², W. Wagner¹⁷⁴, H. Wahlberg⁷³, S. Wahrmond⁴⁵, J. Wakabayashi¹⁰⁴, J. Walder⁷⁴, R. Walker¹⁰¹, W. Walkowiak¹⁴², V. Wallangen^{147a,147b}, C. Wang¹⁵², C. Wang^{34d,87}, F. Wang¹⁷², H. Wang¹⁵, H. Wang⁴¹, J. Wang⁴³, J. Wang¹⁵¹, K. Wang⁸⁹, R. Wang⁶, S.M. Wang¹⁵², T. Wang²², T. Wang³⁶, X. Wang¹⁷⁵, C. Wanotayaroj¹¹⁷, A. Warburton⁸⁹, C.P. Ward²⁹, D.R. Wardrope⁸⁰, A. Washbrook⁴⁷, P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵¹, M.F. Watson¹⁸, G. Watts¹³⁹, S. Watts⁸⁶, B.M. Waugh⁸⁰, S. Webb⁸⁶, M.S. Weber¹⁷, S.W. Weber¹⁷³, J.S. Webster⁶, A.R. Weidberg¹²¹, B. Weinert⁶², J. Weingarten⁵⁵, C. Weiser⁴⁹, H. Weits¹⁰⁸, P.S. Wells³¹, T. Wenaus²⁶, T. Wengler³¹, S. Wenig³¹, N. Wermes²², M. Werner⁴⁹, P. Werner³¹, M. Wessels^{59a}, J. Wetter¹⁶², K. Whalen¹¹⁷, A.M. Wharton⁷⁴, A. White⁸, M.J. White¹, R. White^{33b}, S. White^{125a,125b}, D. Whiteson⁶⁶, F.J. Wickens¹³², W. Wiedenmann¹⁷², M. Wielers¹³², P. Wienemann²², C. Wiglesworth³⁷, L.A.M. Wiik-Fuchs²², A. Wildauer¹⁰², H.G. Wilkens³¹, H.H. Williams¹²³, S. Williams¹⁰⁸, C. Willis⁹², S. Willocq⁸⁸, J.A. Wilson¹⁸, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁷, B.T. Winter²², M. Wittgen¹⁴⁴, J. Wittkowski¹⁰¹, S.J. Wollstadt⁸⁵, M.W. Wolter⁴⁰, H. Wolters^{127a,127c}, B.K. Wosiek⁴⁰, J. Wotschack³¹, M.J. Woudstra⁸⁶, K.W. Wozniak⁴⁰, M. Wu⁵⁶, M. Wu³², S.L. Wu¹⁷², X. Wu⁵⁰, Y. Wu⁹¹, T.R. Wyatt⁸⁶, B.M. Wynne⁴⁷, S. Xella³⁷, D. Xu^{34a}, L. Xu²⁶, B. Yabsley¹⁵¹, S. Yacoub^{146a}, R. Yakabe⁶⁹, D. Yamaguchi¹⁵⁸, Y. Yamaguchi¹¹⁹, A. Yamamoto⁶⁸, S. Yamamoto¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰⁴, Y. Yamazaki⁶⁹, Z. Yan²³, H. Yang^{34e}, H. Yang¹⁷², Y. Yang¹⁵², Z. Yang¹⁴, W.-M. Yao¹⁵, Y.C. Yap⁸², Y. Yasu⁶⁸, E. Yatsenko⁵, K.H. Yau Wong²², J. Ye⁴¹, S. Ye²⁶, I. Yeletsikh⁶⁷, A.L. Yen⁵⁸, E. Yildirim⁴³, K. Yorita¹⁷⁰, R. Yoshida⁶, K. Yoshihara¹²³, C. Young¹⁴⁴, C.J.S. Young³¹, S. Youssef²³, D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁹¹, J. Yu⁶⁵, L. Yuan⁶⁹, S.P.Y. Yuen²², I. Yusuff^{29,an}, B. Zabinski⁴⁰, R. Zaidan^{34d}, A.M. Zaitsev^{131,ac}, N. Zakharchuk⁴³, J. Zalieckas¹⁴, A. Zaman¹⁴⁹, S. Zambito⁵⁸, L. Zanello^{133a,133b}, D. Zanzi⁹⁰, C. Zeitnitz¹⁷⁴, M. Zeman¹²⁹, A. Zemla^{39a}, J.C. Zeng¹⁶⁵, Q. Zeng¹⁴⁴, K. Zengel²⁴, O. Zenin¹³¹, T. Ženiš^{145a}, D. Zerwas¹¹⁸, D. Zhang⁹¹, F. Zhang¹⁷², G. Zhang^{34b,z}, H. Zhang^{34c}, J. Zhang⁶, L. Zhang⁴⁹, R. Zhang²², R. Zhang^{34b,ao}, X. Zhang^{34d}, Z. Zhang¹¹⁸, X. Zhao⁴¹, Y. Zhao^{34d,118}, Z. Zhao^{34b}, A. Zhemchugov⁶⁷, J. Zhong¹²¹, B. Zhou⁹¹, C. Zhou⁴⁶, L. Zhou³⁶, L. Zhou⁴¹, M. Zhou¹⁴⁹, N. Zhou^{34f}, C.G. Zhu^{34d}, H. Zhu^{34a}, J. Zhu⁹¹, Y. Zhu^{34b}, X. Zhuang^{34a}, K. Zhukov⁹⁷, A. Zibell¹⁷³, D. Zieminska⁶², N.I. Zimine⁶⁷, C. Zimmermann⁸⁵, S. Zimmermann⁴⁹, Z. Zinonos⁵⁵, M. Zinser⁸⁵, M. Ziolkowski¹⁴², L. Živković¹³, G. Zobernig¹⁷², A. Zoccoli^{21a,21b}, M. zur Nedden¹⁶, G. Zurzolo^{105a,105b}, L. Zwalinski³¹

- ¹ Department of Physics, University of Adelaide, Adelaide, Australia
- ² Physics Department, SUNY Albany, Albany, NY, United States
- ³ Department of Physics, University of Alberta, Edmonton, AB, Canada
- ⁴ (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
- ⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
- ⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
- ⁷ Department of Physics, University of Arizona, Tucson, AZ, United States
- ⁸ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
- ⁹ Physics Department, University of Athens, Athens, Greece
- ¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece
- ¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹² Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
- ¹³ Institute of Physics, University of Belgrade, Belgrade, Serbia
- ¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
- ¹⁶ Department of Physics, Humboldt University, Berlin, Germany
- ¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (e) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ²⁰ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ²¹ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- ²² Physikalisches Institut, University of Bonn, Bonn, Germany
- ²³ Department of Physics, Boston University, Boston, MA, United States
- ²⁴ Department of Physics, Brandeis University, Waltham, MA, United States
- ²⁵ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁶ Physics Department, Brookhaven National Laboratory, Upton, NY, United States
- ²⁷ (a) Transilvania University of Brasov, Brasov; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
- ²⁸ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁹ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ³⁰ Department of Physics, Carleton University, Ottawa, ON, Canada
- ³¹ CERN, Geneva, Switzerland
- ³² Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
- ³³ (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³⁴ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai^{ap}; (f) Physics Department, Tsinghua University, Beijing 100084, China
- ³⁵ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁶ Nevis Laboratory, Columbia University, Irvington, NY, United States
- ³⁷ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ³⁸ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁹ (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ⁴⁰ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- ⁴¹ Physics Department, Southern Methodist University, Dallas, TX, United States
- ⁴² Physics Department, University of Texas at Dallas, Richardson, TX, United States
- ⁴³ DESY, Hamburg and Zeuthen, Germany
- ⁴⁴ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁵ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁶ Department of Physics, Duke University, Durham, NC, United States
- ⁴⁷ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁸ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁹ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁵⁰ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵¹ (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵² (a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵³ II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵⁴ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁵ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁶ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁷ Department of Physics, Hampton University, Hampton, VA, United States
- ⁵⁸ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- ⁵⁹ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁶⁰ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶¹ (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶² Department of Physics, Indiana University, Bloomington, IN, United States
- ⁶³ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶⁴ University of Iowa, Iowa City, IA, United States
- ⁶⁵ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- ⁶⁶ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
- ⁶⁷ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁸ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁹ Graduate School of Science, Kobe University, Kobe, Japan
- ⁷⁰ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁷¹ Kyoto University of Education, Kyoto, Japan

- ⁷² Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷³ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁴ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷⁵ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁶ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁷ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁸ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁹ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁸⁰ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁸¹ Louisiana Tech University, Ruston, LA, United States
- ⁸² Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸³ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁴ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸⁵ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁶ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁷ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁸ Department of Physics, University of Massachusetts, Amherst, MA, United States
- ⁸⁹ Department of Physics, McGill University, Montreal, QC, Canada
- ⁹⁰ School of Physics, University of Melbourne, Victoria, Australia
- ⁹¹ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁹² Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁹³ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁴ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹⁵ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹⁶ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁷ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- ⁹⁸ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁹ National Research Nuclear University MEPhI, Moscow, Russia
- ¹⁰⁰ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹⁰¹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰² Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰³ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰⁴ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁵ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁶ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁷ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁸ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁹ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹¹⁰ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹¹ Department of Physics, New York University, New York, NY, United States
- ¹¹² Ohio State University, Columbus, OH, United States
- ¹¹³ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹⁴ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- ¹¹⁵ Department of Physics, Oklahoma State University, Stillwater, OK, United States
- ¹¹⁶ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁷ Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- ¹¹⁸ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹¹⁹ Graduate School of Science, Osaka University, Osaka, Japan
- ¹²⁰ Department of Physics, University of Oslo, Oslo, Norway
- ¹²¹ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²² ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²³ Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- ¹²⁴ National Research Centre “Kurchatov Institute”, B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ¹²⁵ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁶ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- ¹²⁷ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁸ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁹ Czech Technical University in Prague, Praha, Czech Republic
- ¹³⁰ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹³¹ State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- ¹³² Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³³ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹³⁴ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁵ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹³⁶ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
- ¹³⁷ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- ¹³⁸ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- ¹³⁹ Department of Physics, University of Washington, Seattle, WA, United States
- ¹⁴⁰ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴¹ Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴² Fachbereich Physik, Universität Siegen, Siegen, Germany
- ¹⁴³ Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- ¹⁴⁴ SLAC National Accelerator Laboratory, Stanford, CA, United States
- ¹⁴⁵ ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

- ¹⁴⁶ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁷ ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- ¹⁴⁸ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁴⁹ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- ¹⁵⁰ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵¹ School of Physics, University of Sydney, Sydney, Australia
- ¹⁵² Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵³ Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- ¹⁵⁴ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵⁵ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁶ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁷ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁸ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁹ Department of Physics, University of Toronto, Toronto, ON, Canada
- ¹⁶⁰ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
- ¹⁶¹ Faculty of Pure and Applied Sciences, and Center for Integrated in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- ¹⁶² Department of Physics and Astronomy, Tufts University, Medford, MA, United States
- ¹⁶³ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁴ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁵ Department of Physics, University of Illinois, Urbana, IL, United States
- ¹⁶⁶ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁶⁷ Department of Physics, University of British Columbia, Vancouver, BC, Canada
- ¹⁶⁸ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
- ¹⁶⁹ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷⁰ Waseda University, Tokyo, Japan
- ¹⁷¹ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷² Department of Physics, University of Wisconsin, Madison, WI, United States
- ¹⁷³ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁴ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁵ Department of Physics, Yale University, New Haven, CT, United States
- ¹⁷⁶ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁷ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

^a Also at Department of Physics, King's College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^c Also at Novosibirsk State University, Novosibirsk, Russia.

^d Also at TRIUMF, Vancouver, BC, Canada.

^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States.

^f Also at Department of Physics, California State University, Fresno, CA, United States.

^g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

^h Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

ⁱ Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

^j Also at Tomsk State University, Tomsk, Russia.

^k Also at Università di Napoli Parthenope, Napoli, Italy.

^l Also at Institute of Particle Physics (IPP), Canada.

^m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

ⁿ Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

^o Also at Louisiana Tech University, Ruston, LA, United States.

^p Also at Institutio Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.

^q Also at Graduate School of Science, Osaka University, Osaka, Japan.

^r Also at Department of Physics, National Tsing Hua University, Taiwan.

^s Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.

^t Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^u Also at CERN, Geneva, Switzerland.

^v Also at Georgian Technical University (GTU), Tbilisi, Georgia.

^w Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

^x Also at Manhattan College, New York, NY, United States.

^y Also at Hellenic Open University, Patras, Greece.

^z Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{aa} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{ab} Also at School of Physics, Shandong University, Shandong, China.

^{ac} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^{ad} Also at Section de Physique, Université de Genève, Geneva, Switzerland.

^{ae} Also at International School for Advanced Studies (SISSA), Trieste, Italy.

^{af} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

^{ag} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

^{ah} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

^{ai} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

^{aj} Also at National Research Nuclear University MEPhI, Moscow, Russia.

^{ak} Also at Department of Physics, Stanford University, Stanford, CA, United States.

^{al} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

^{am} Also at Flensburg University of Applied Sciences, Flensburg, Germany.

^{an} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

^{ao} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^{ap} Also affiliated with PKU-CHEP.

* Deceased.